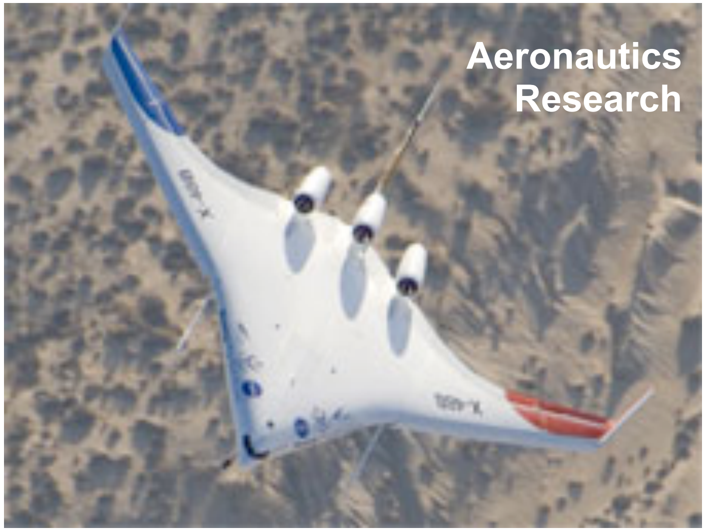
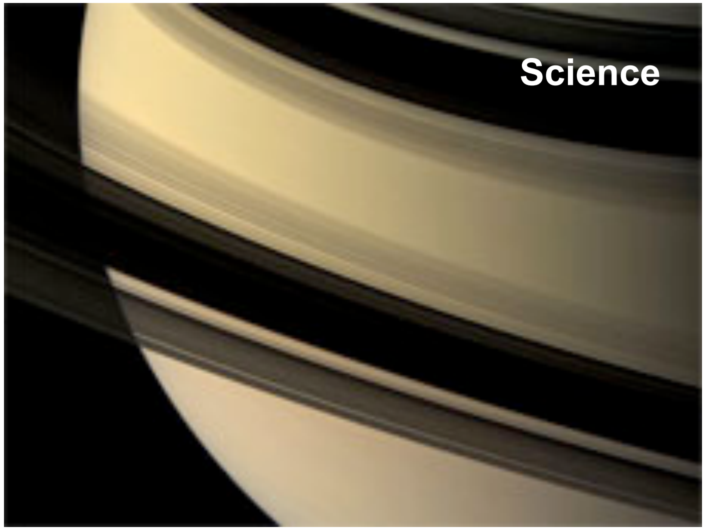
Nanotechnology
From Science Fiction to Reality

Mia Siochi

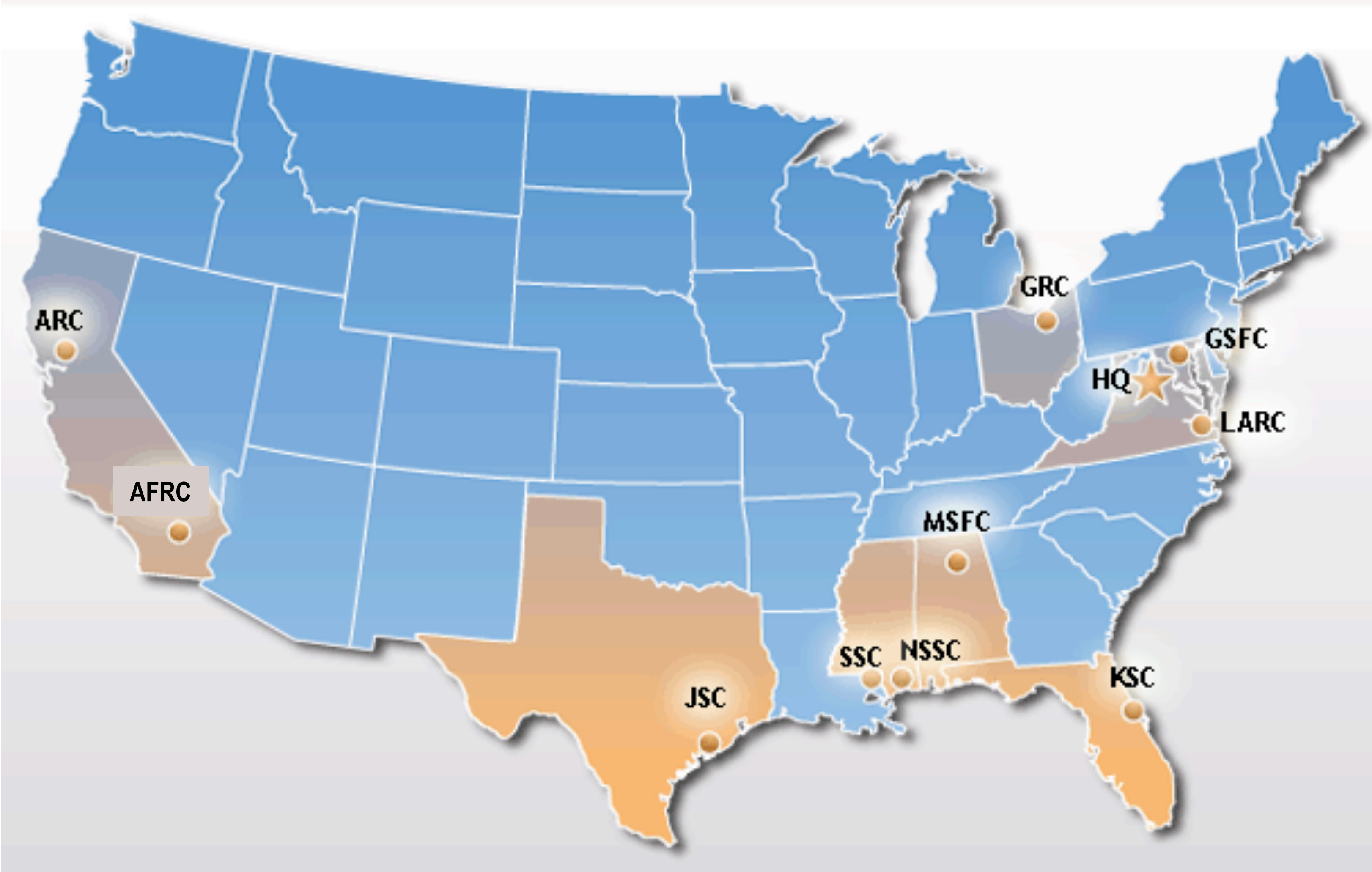
Virginia Tech MII Seminar Series
March 2, 2016

NASA Missions





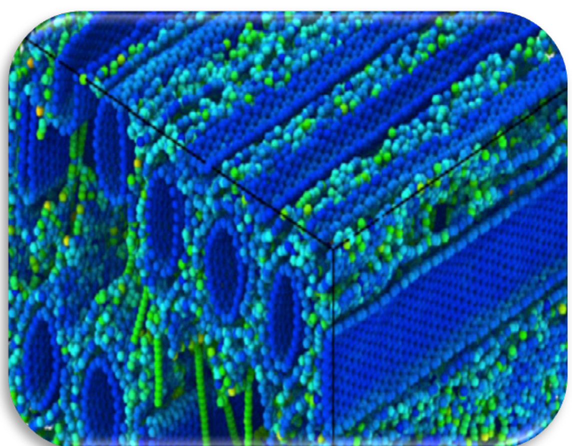
NASA Centers

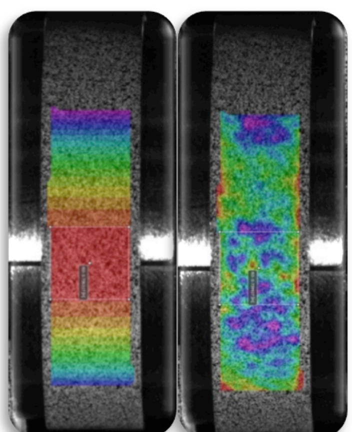


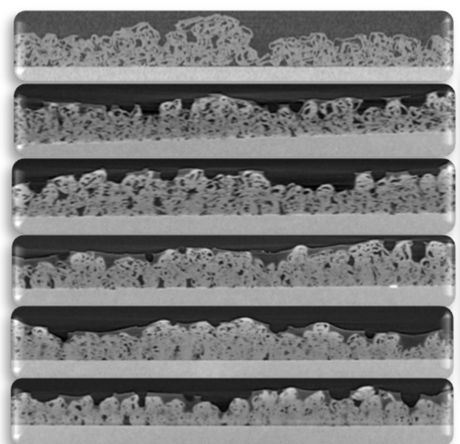
Examples of Transitioning Emerging Technologies

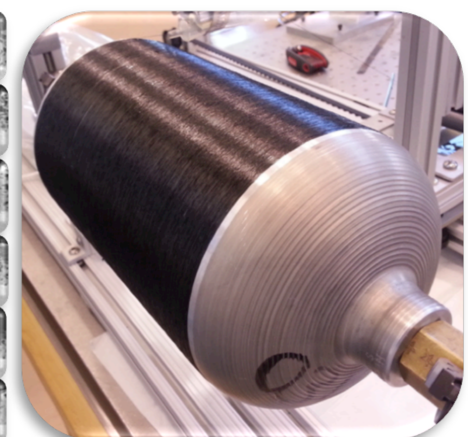
- Structural Carbon Nanotube Composites
- 3D Printing of Multifunctional Components
- Nanoengineered Surfaces for Insect Residue Adhesion Mitigation

Structural Nanomaterials for Aerospace Applications









Structural CNT Team

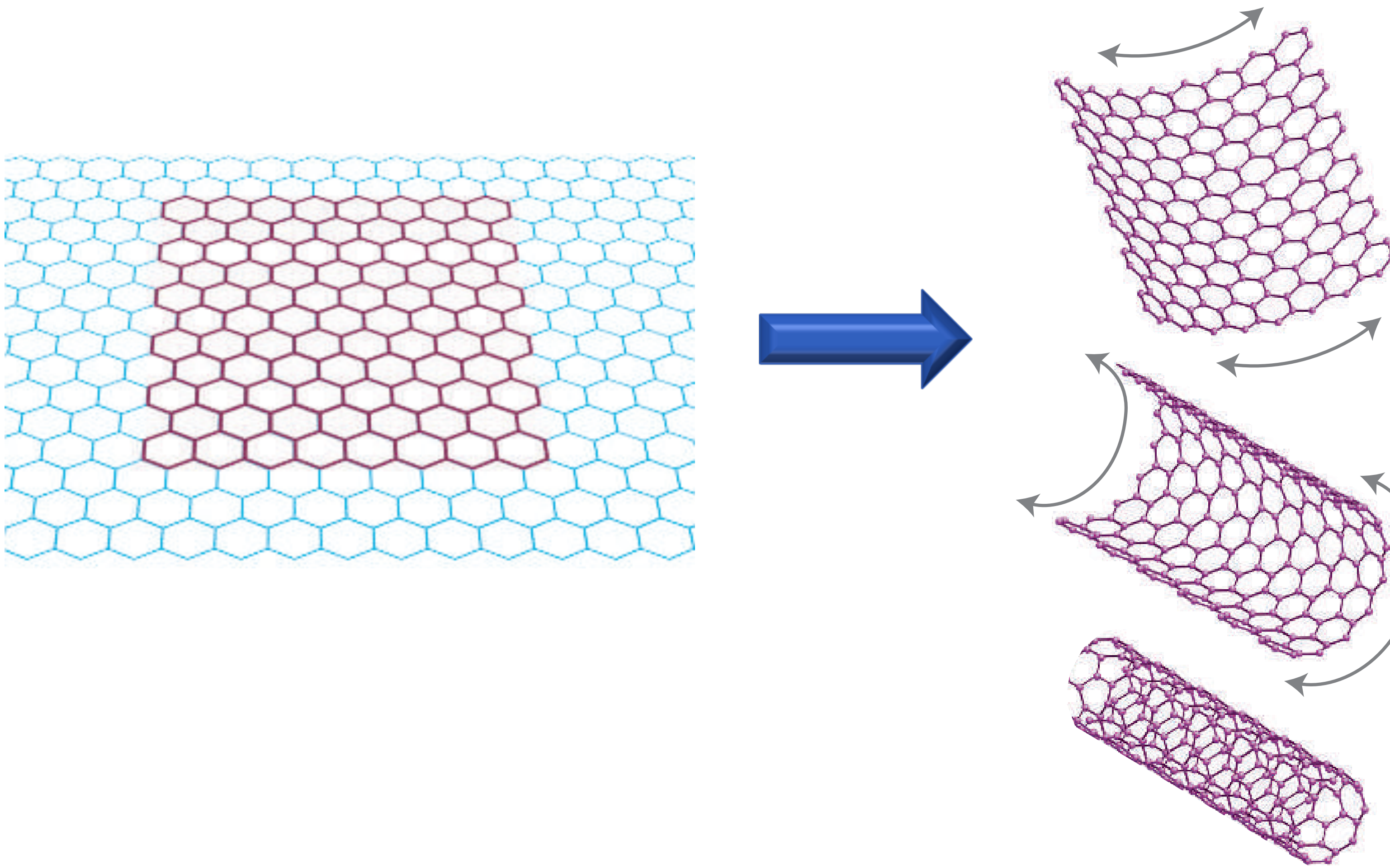
Not in photo:

LaRC: Dr. John Connell
Dr. James Ratcliffe
Dr. Steve Scotti
Dr. Jamshid Samareh
Mr. Sean Britton
Mr. Hoa Luong

Univ. Utah: Dr. Mike Czabaj

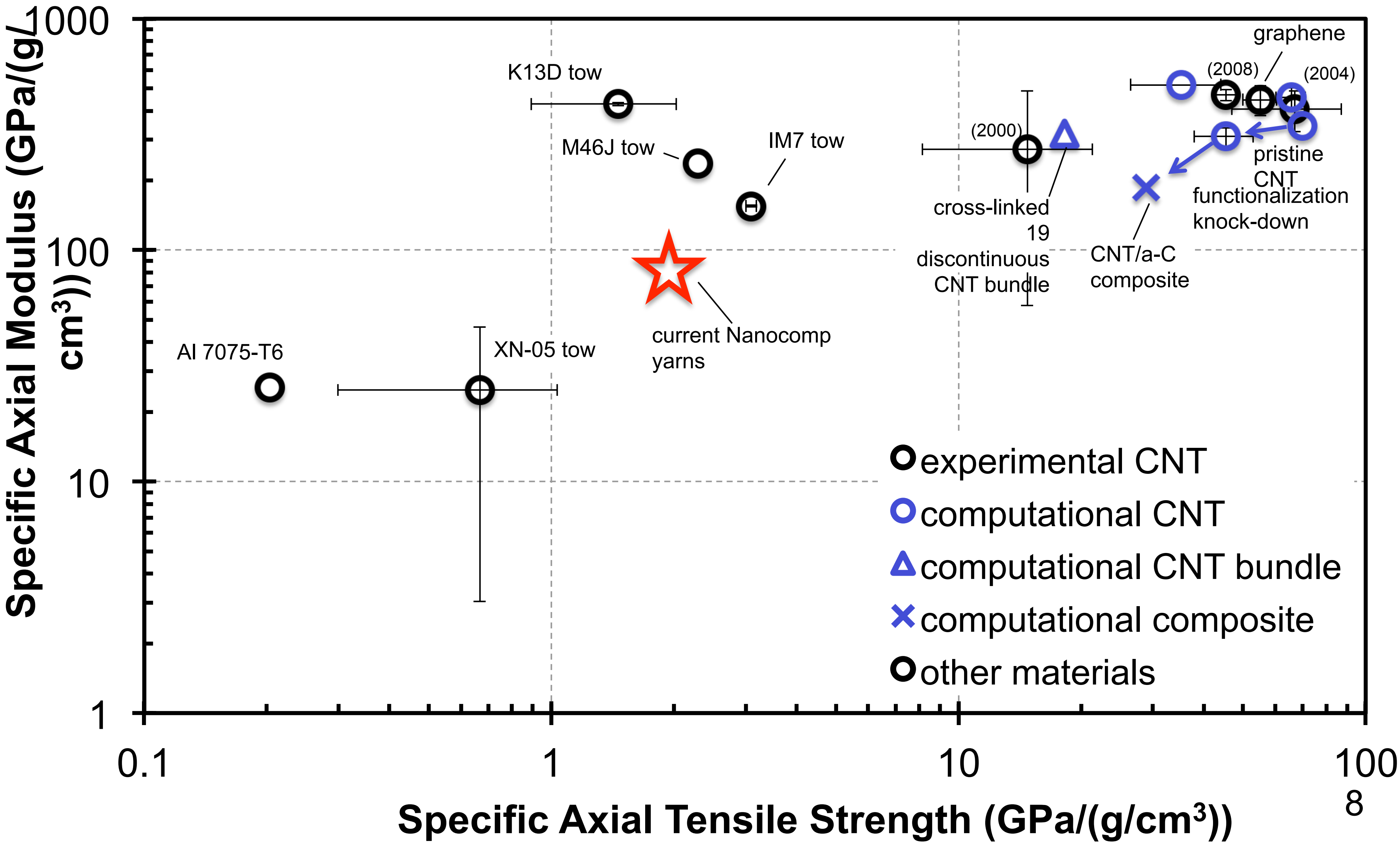
"The key to building a great product is building a great team first. To me, great teams aren't bound by roles, but they're driven by moving forward."— Alan Page

Carbon Nanotubes

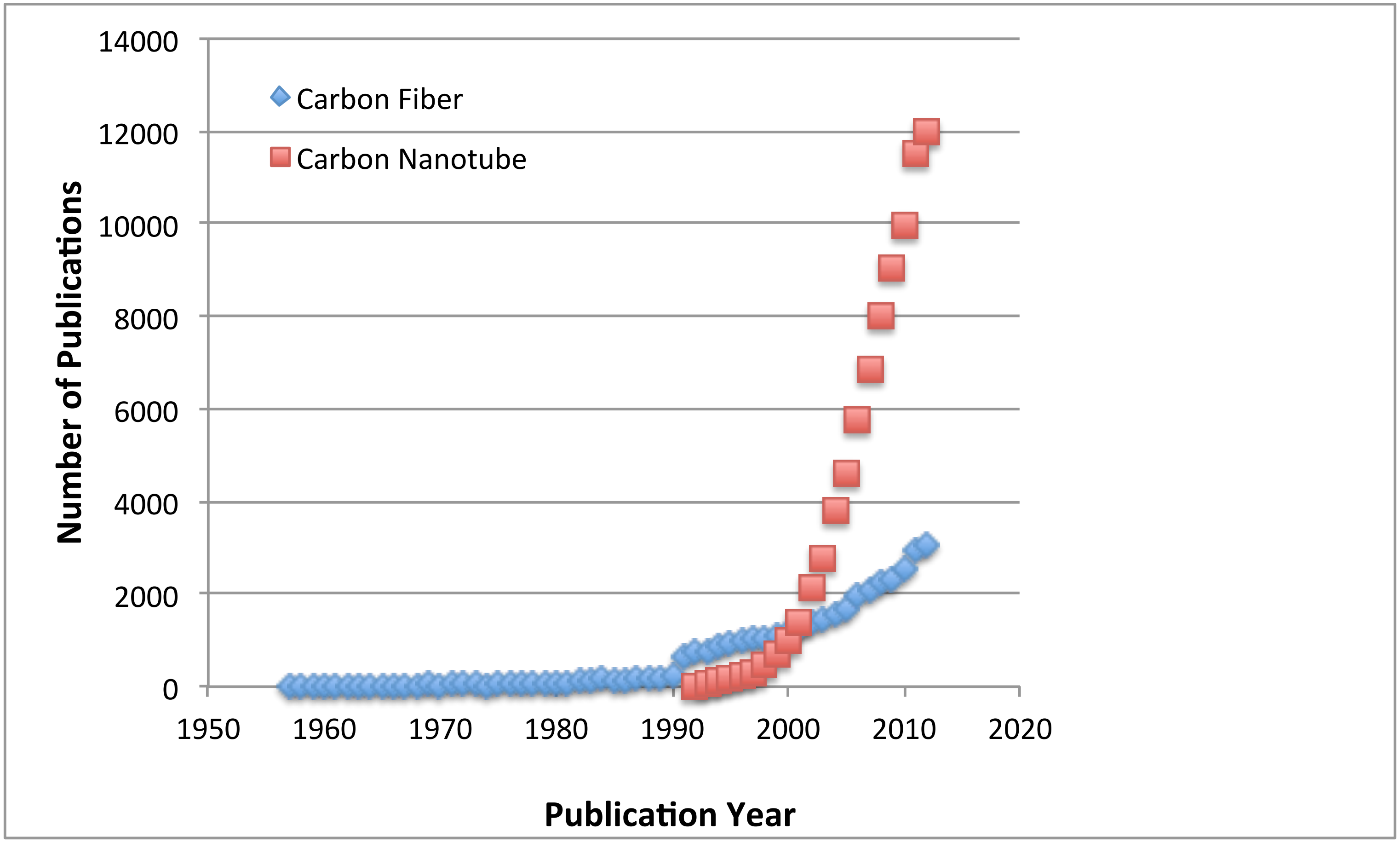


Geim, A. K. and Novoselov, K. S., “The Rise of Graphene,” Nautre Materials, 6, 183-191, 2007.

Mechanical Properties of Aerospace Materials



Comparison of CFRP and CNT Literature



- Compared to SOA lightweight structural materials (CFRP), there has been considerably greater attention paid to CNTs since its discovery in 1991.

Statistics derived from Web of Science data, Siochi, April 2013.

Carbon Nanotube Nanocomposites

CNT Dispersion Work (2000-2008)

- Analogous to chopped fiber composites
- Limited by material supply and solubility
- Very low volume fraction (<5%)
- Limited improvement over matrix mechanical properties
- Focus on electrical/multifunctional properties
- Output: Papers, presentations, patents

CNT Sheet/Fiber Work (2011-Present)

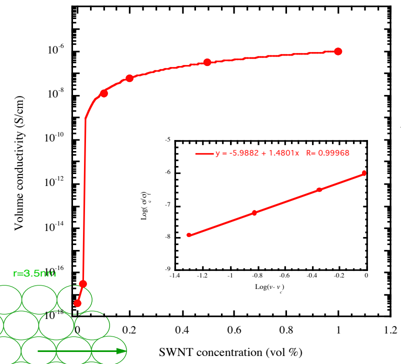
- Analogous to continuous composites
- Material supply is limited but improving (quantity & quality)
- High volume fraction (>60%)
- Near SOA CF composite specific modulus & strength
- Focus on structure
- Output: Flight hardware

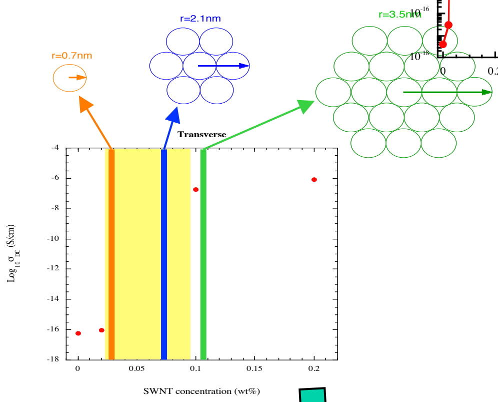
2000 2002 2004 2006 2008 2010 2012 2014 2016

Summary of 2000 - 2008

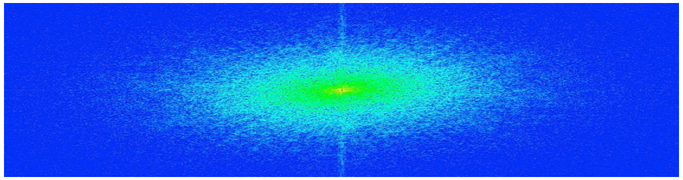
0.02%SWNT-CP2 0.02%SWNT-(β-CN) PI

Observed Differences in Nanocomposite Solution Stability

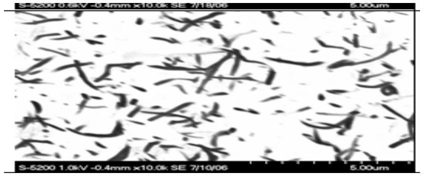


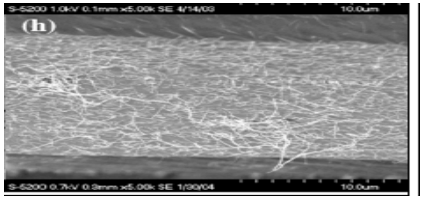


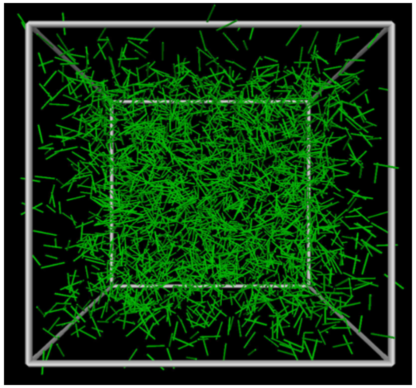
Measured Electrical Conductivity and Percolation Modeling

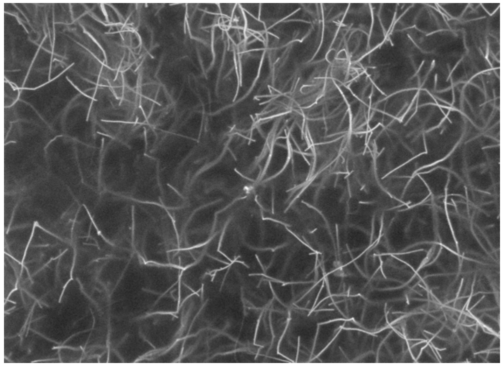


Fast Fourier Transform of HRSEM Image









“Poly-transparent” Imaging

Accelerated Technology Maturation thru Use-inspired Basic Research

Considerations of use?

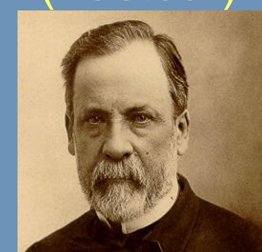
No | Yes

Quest for fundamental understanding?

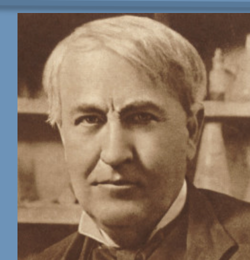
Yes

Pure basic research (Bohr)

Use-inspired basic research (Pasteur)



No

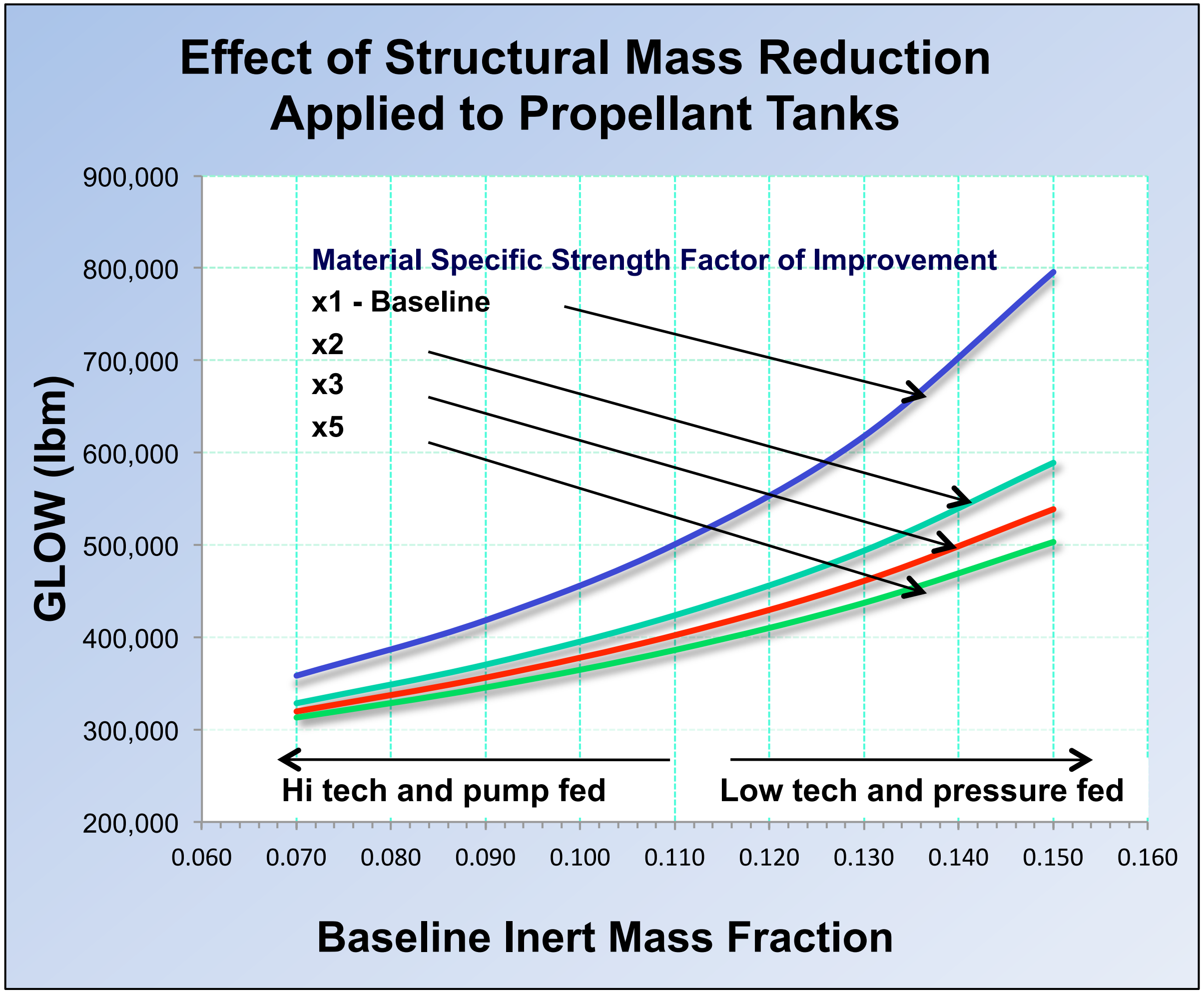


Pure applied research (Edison)

Donald E. Stokes, Pasteur's Quadrant: Basic Science and Technological Innovation, 1997.

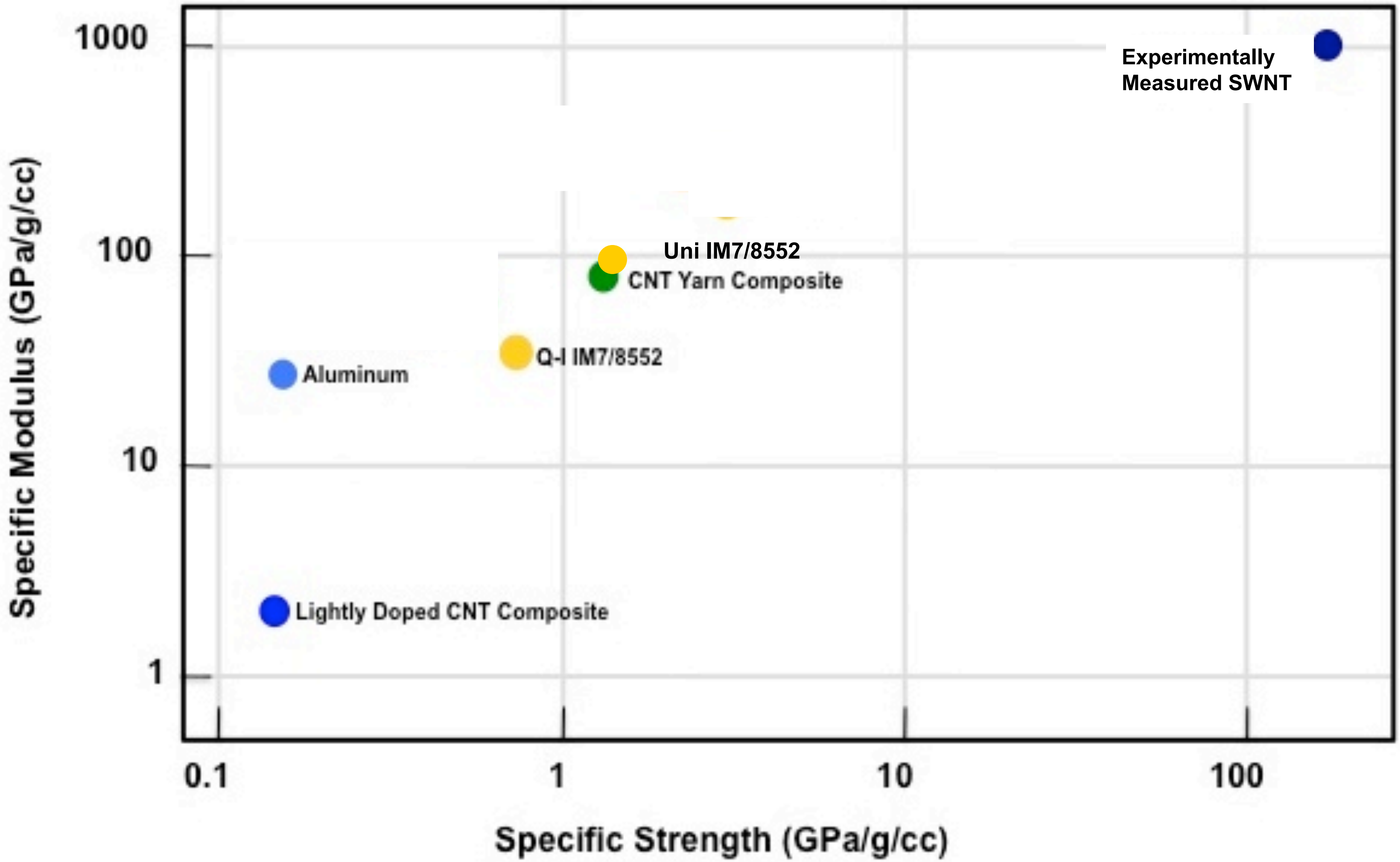
Potential System Weight Savings

Two Stage to Orbit Launch Vehicle Concept



- Baseline Mass Fractions typical for existing cryogenic pump and pressure fed stages
- Weight savings applied to pressurized structures only
- Including other structures and subsystems may show increased benefit
- Low tech pressure fed systems show greatest benefit from reduced structures weight

How is Structural CNT Different?



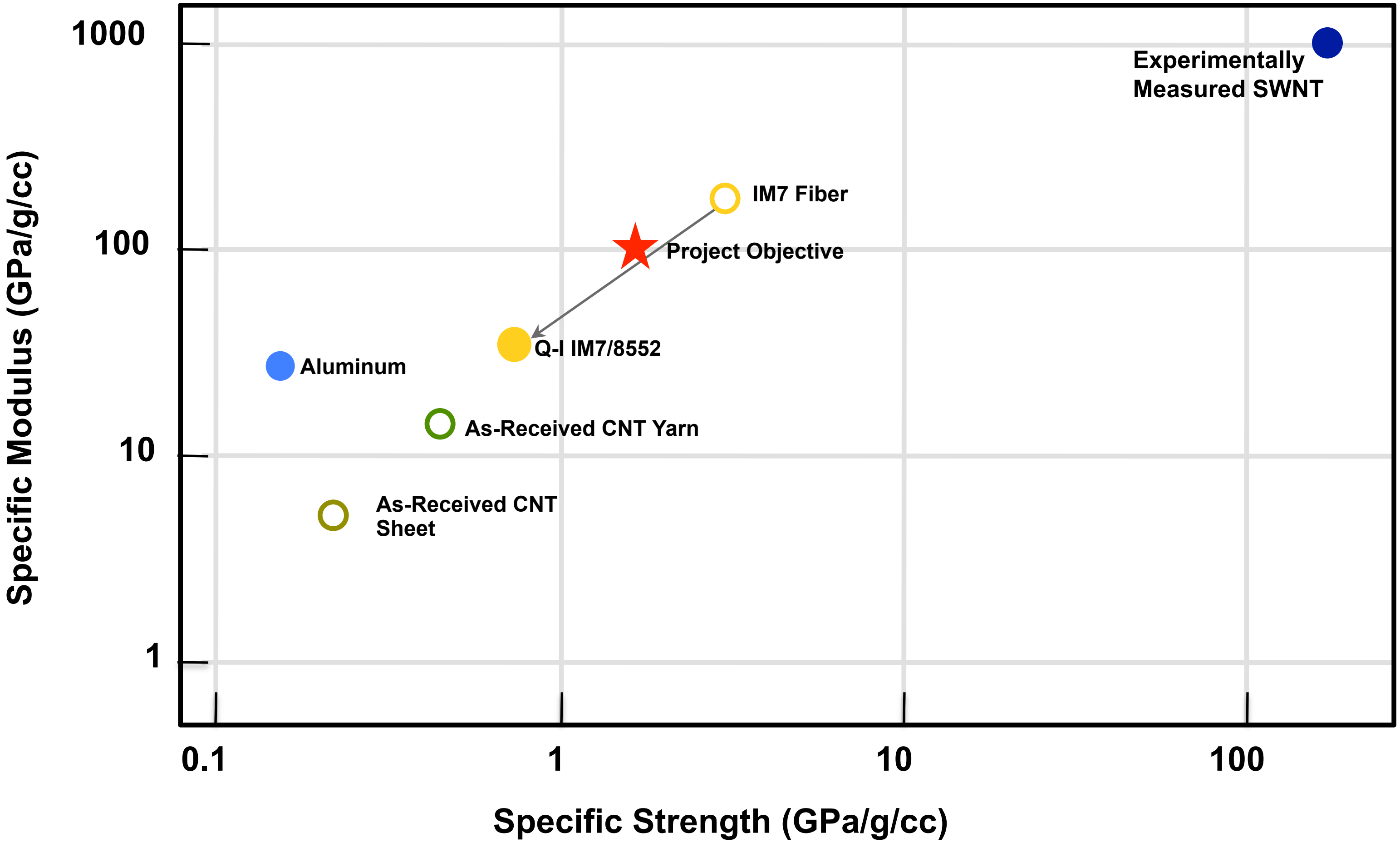
Carbon Nanotube Starting Materials

Sheets

Tapes

Yarns

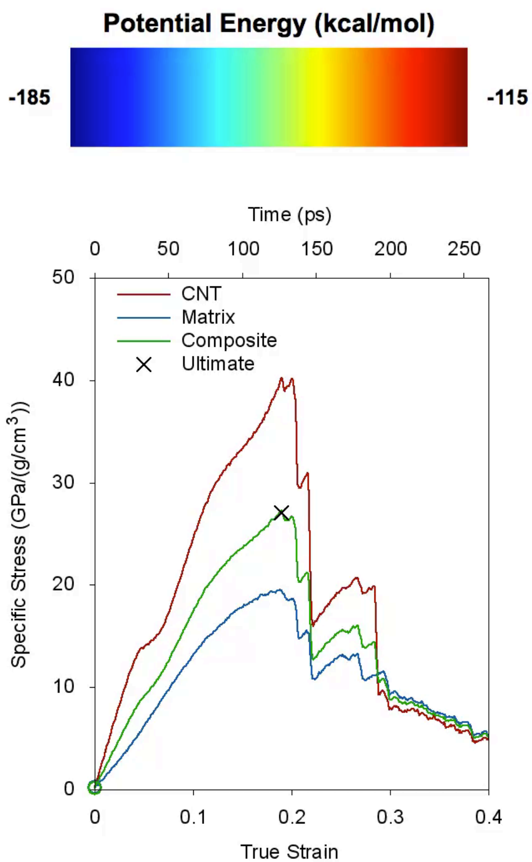
Nano to Macro Challenge

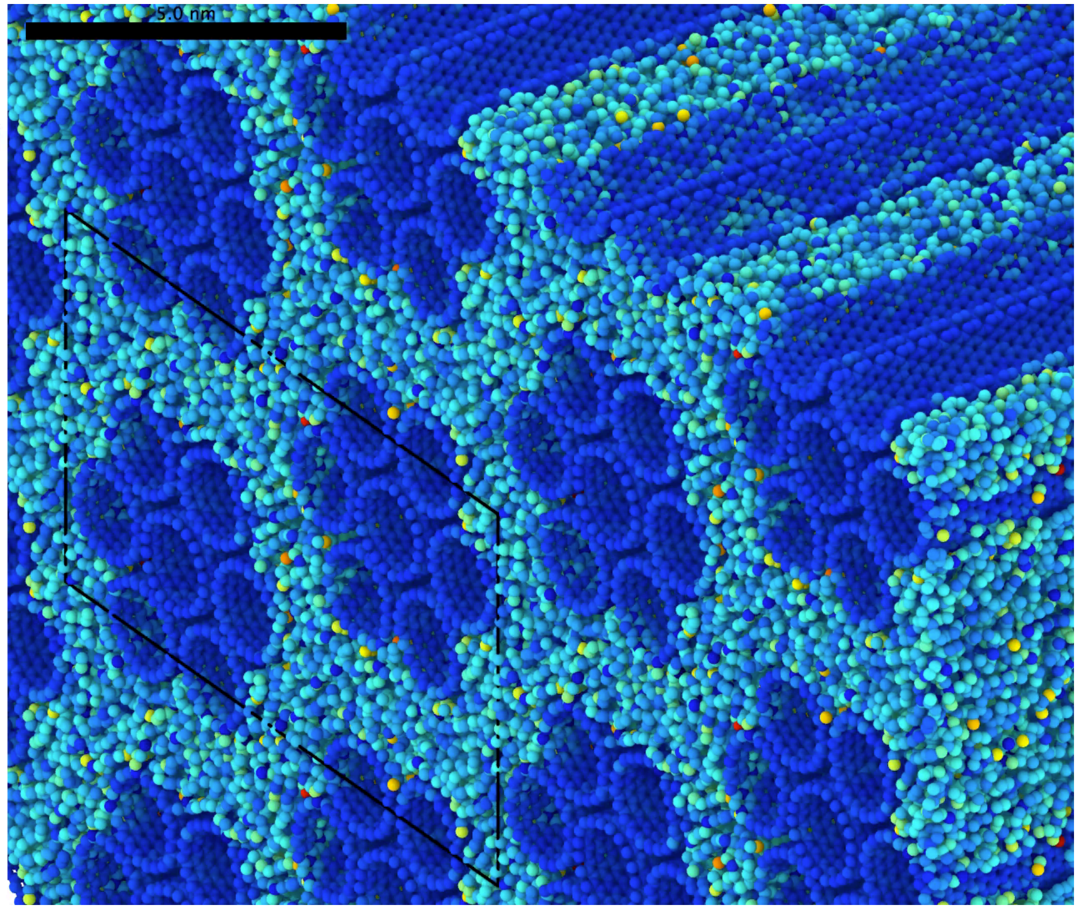


- Available materials have starting mechanical properties inferior to other SOA materials.

Fracture of CNT Composites

ReaxFF Simulation of a SWNT Bundle/Amorphous Carbon Composite





Jensen, Benjamin D., Kristopher E. Wise, and Gregory M. Odegard. "Simulation of mechanical performance limits and failure of carbon nanotube composites." Modelling and Simulation in Materials Science and Engineering 24.2 (2016): 025012.

Modeling of CNT Composite

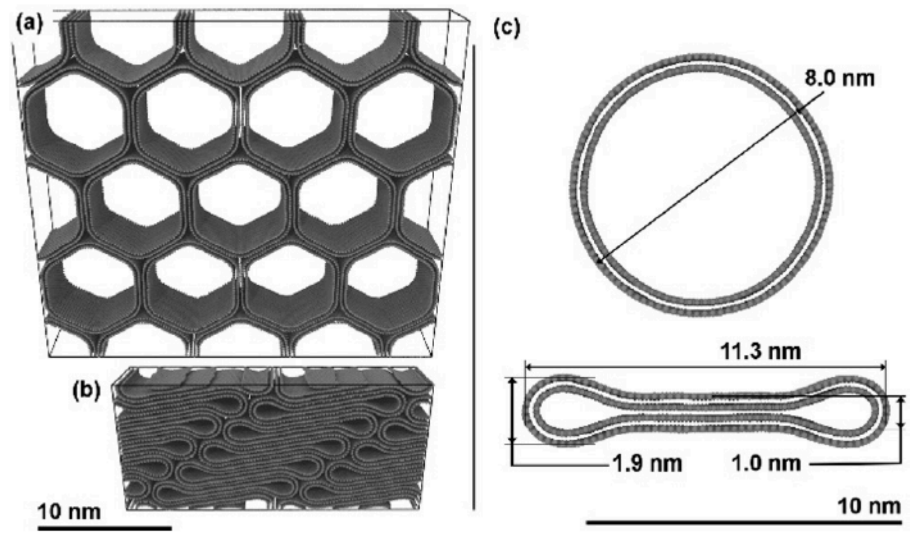
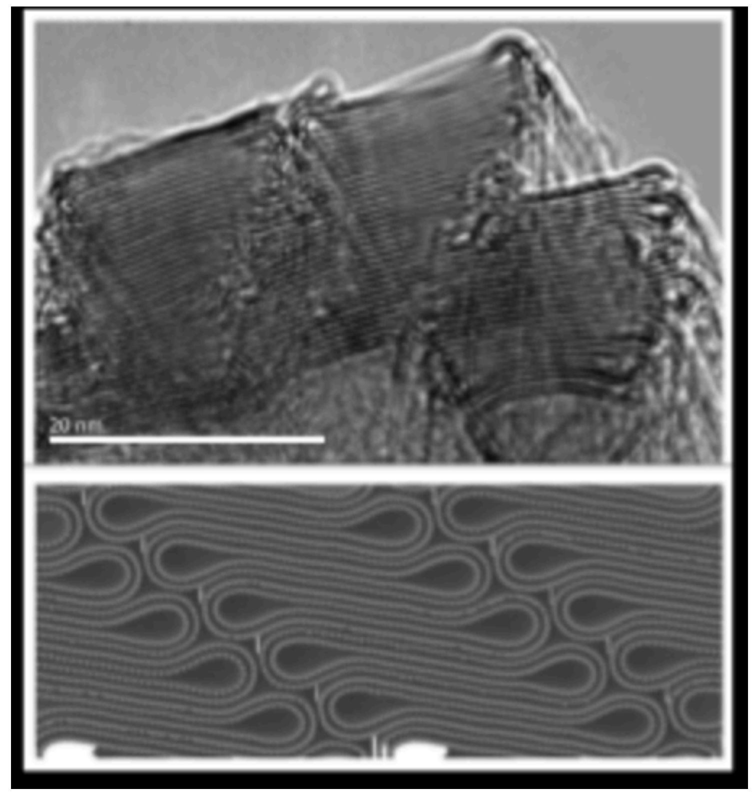
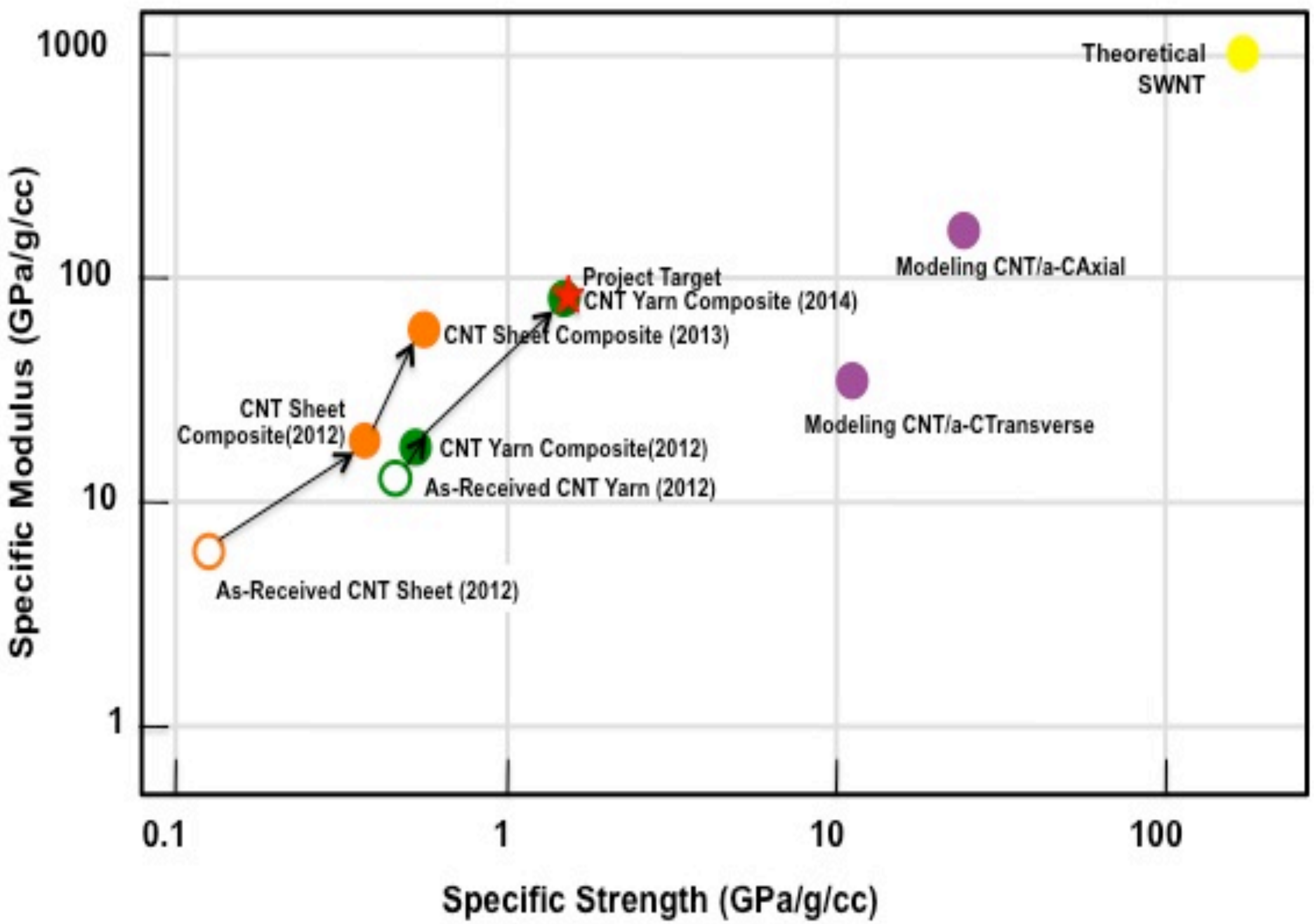


Fig. 5 – Bulk CNT systems consisting of (a) 0% collapsed round CNTs and (b) 100% collapsed CNTs, (c) dimensions of flat and round CNTs in isolation.



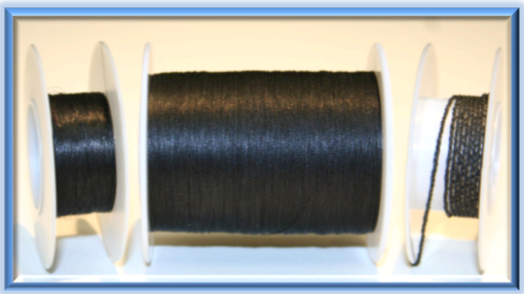
Downes, R.D., Hao, A., Park, J.G., Su, Y.F., Liang, R., Jensen, B.D., Siochi, E.J. and Wise, K.E., 2015. Geometrically constrained self-assembly and crystal packing of flattened and aligned carbon nanotubes. *Carbon*, *93*, pp.953-966.

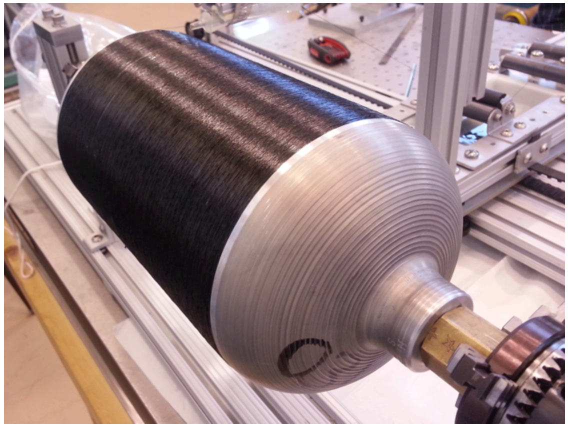
Current State of CNT Composites



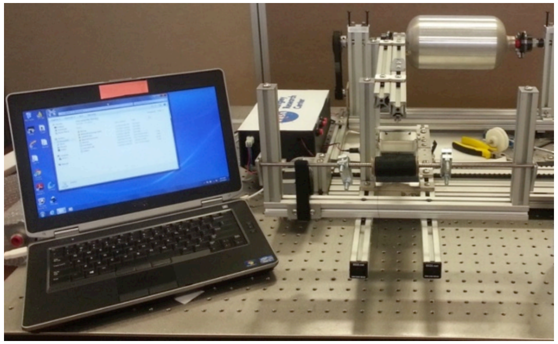
Moving CNT Composites from Lab to COPV Application

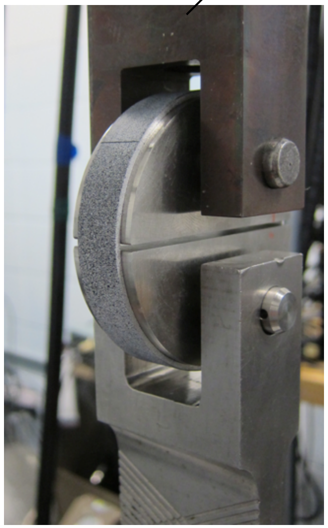
CNT Yarn

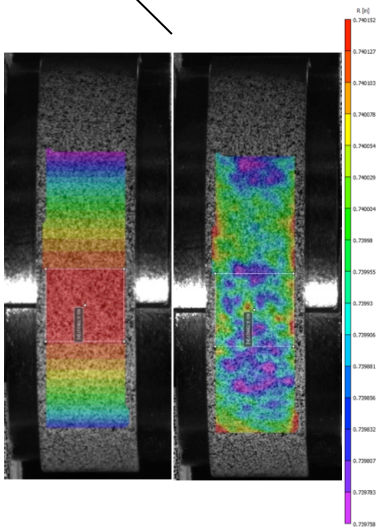




CNT Yarn Composite Overwrapped Pressure Vessel (CNT yarn COPV)

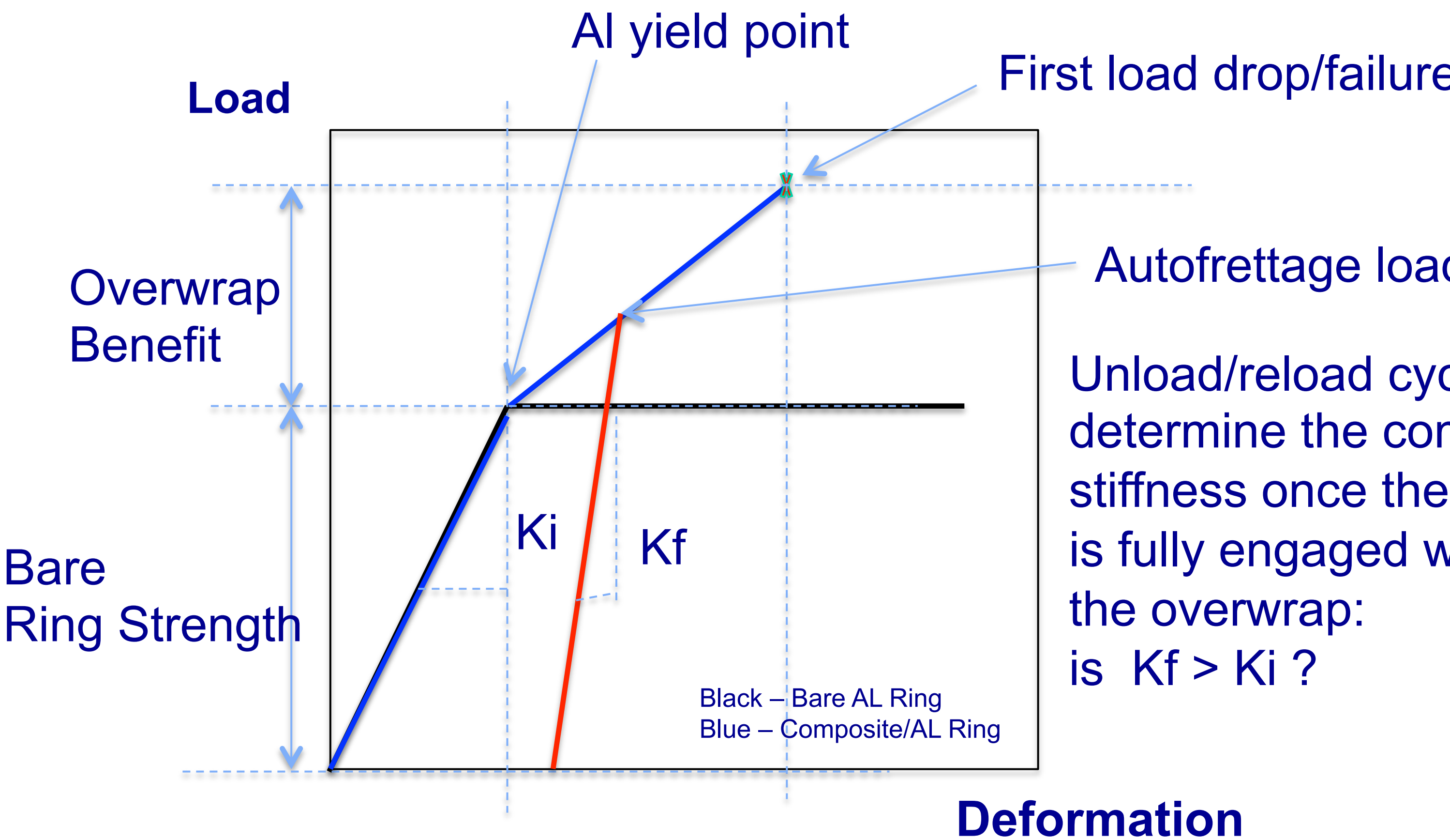






Split Disk Testing

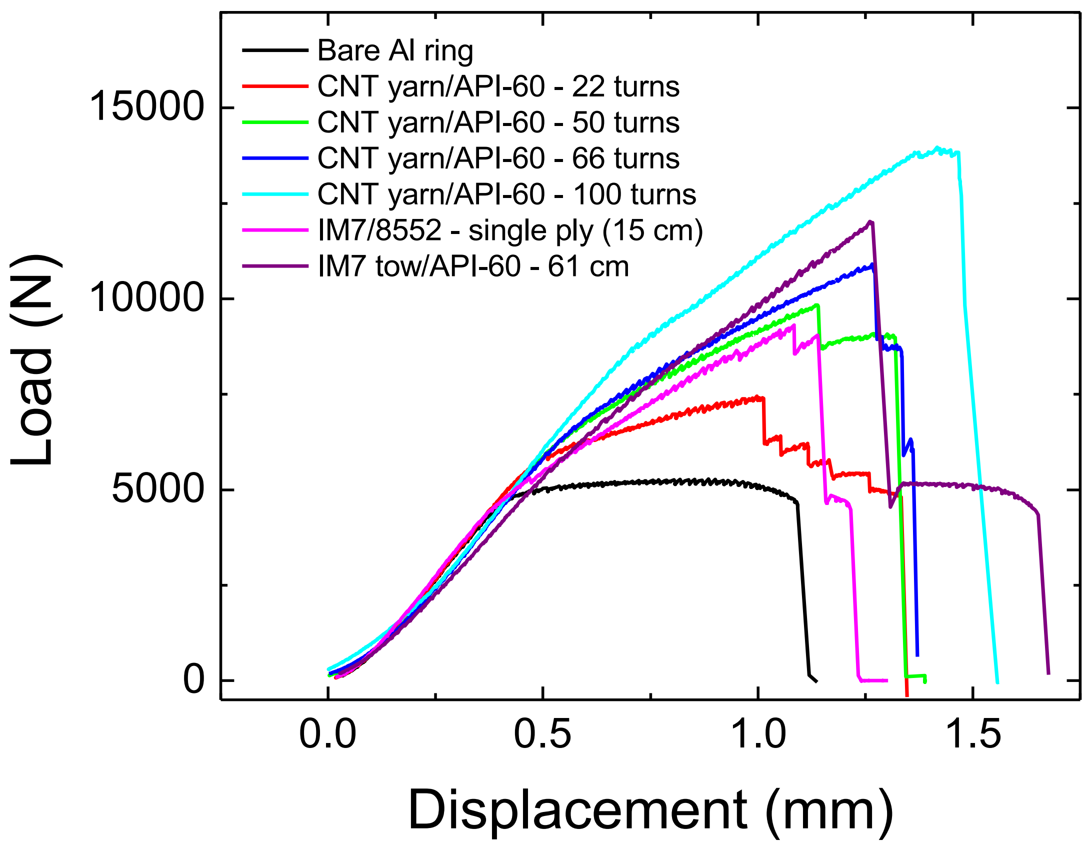
Autofrettage Experiment



Unload/reload cycle: determine the combined stiffness once the Al ring/liner is fully engaged with the overwrap: is Kf > Ki ?

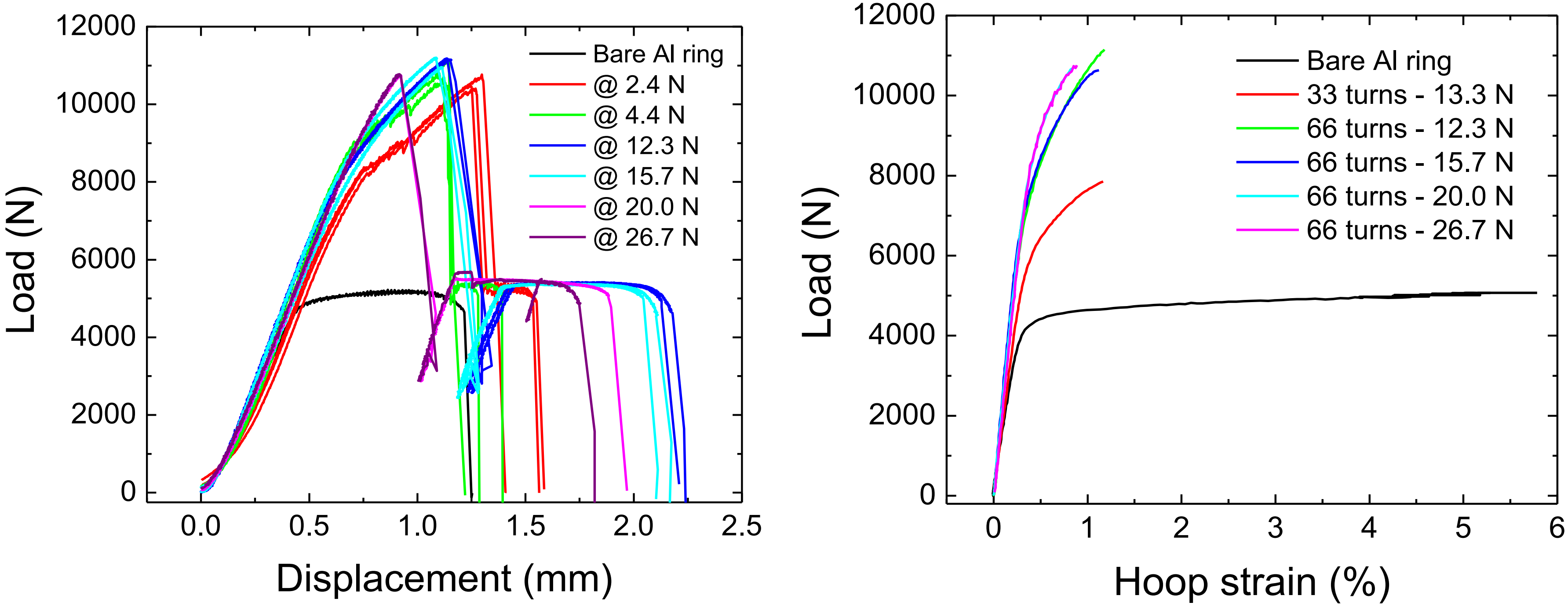
AF Factors: 1.25, 1.5 and 1.75
AF Load = AF Factor x Bare Ring Yield Point

CNT Composite Load-Displacement Curves



Kim, Jae-Woo, Godfrey Sauti, Roberto J. Cano, Russell A. Wincheski, James G. Ratcliffe, Michael Czabaj, Nathaniel W. Gardner, and Emilie J. Siochi. "Assessment of Carbon Nanotube Yarns as Reinforcement for Composite Overwrapped Pressure Vessels." Composites Part A: Applied Science and Manufacturing (2016).

Effect of Windng Tension on Mechanical Performance



Winding tension ⇧ → slope ⇧

Winding tension ⇧ → ultimate breaking load X

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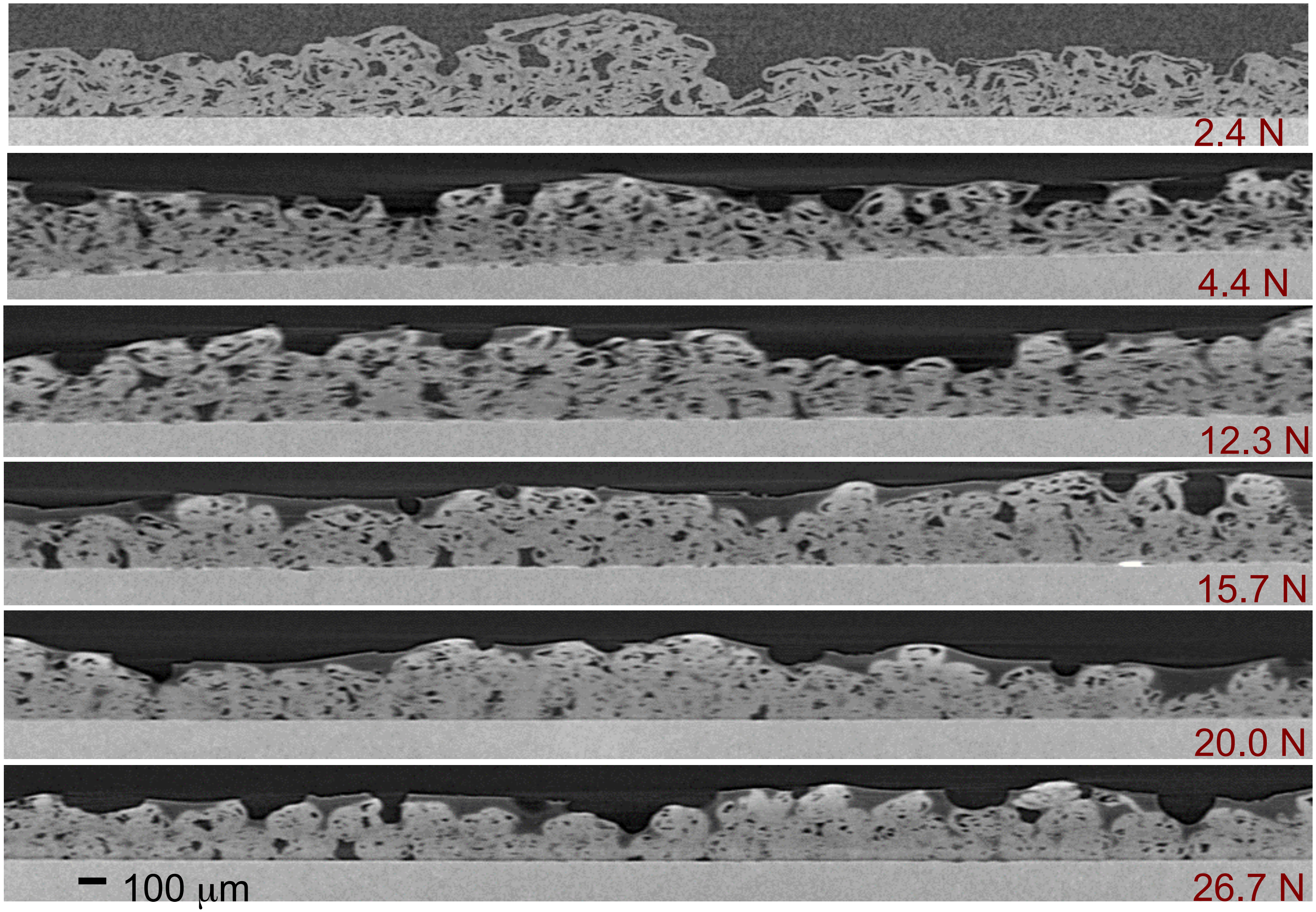
Effect of Winding Tension on CNT Reinforcement



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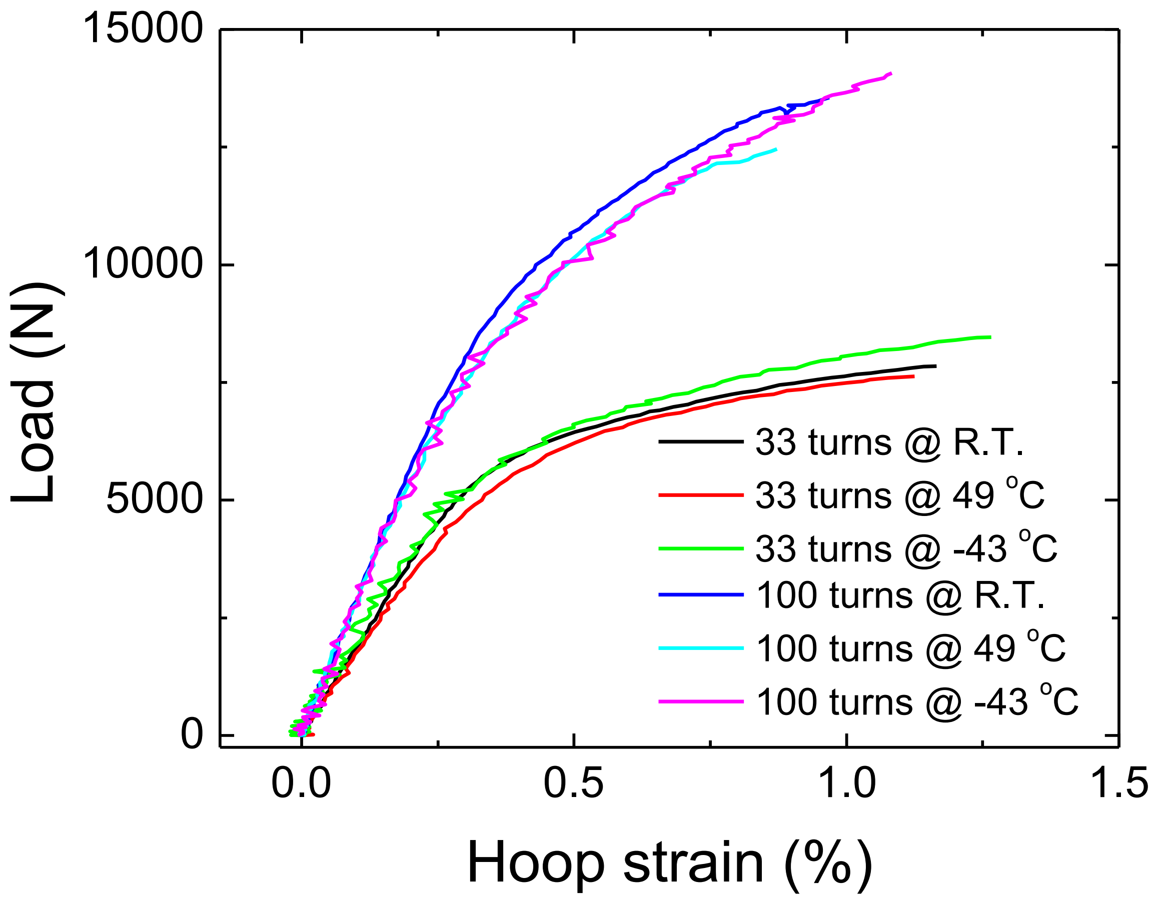
Mechanical Performance of CNT Composites under Static Loading



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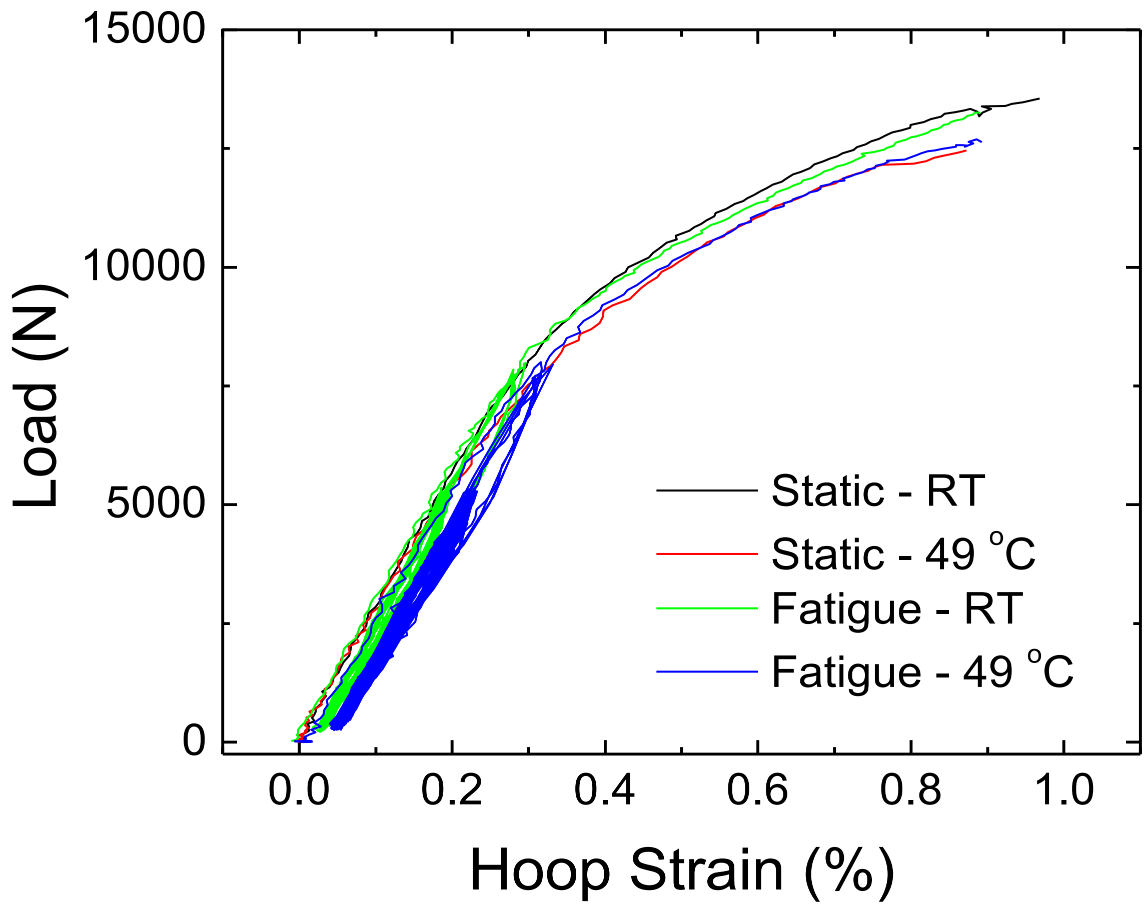
Mechanical Performance of CNT Composites under Fatigue Cycling

- Fatigue: 4 x (0 N, proof load, 222 N, 14 cycles of 222 N/5338 N/222 N) → total 60 load cycle → load to failure



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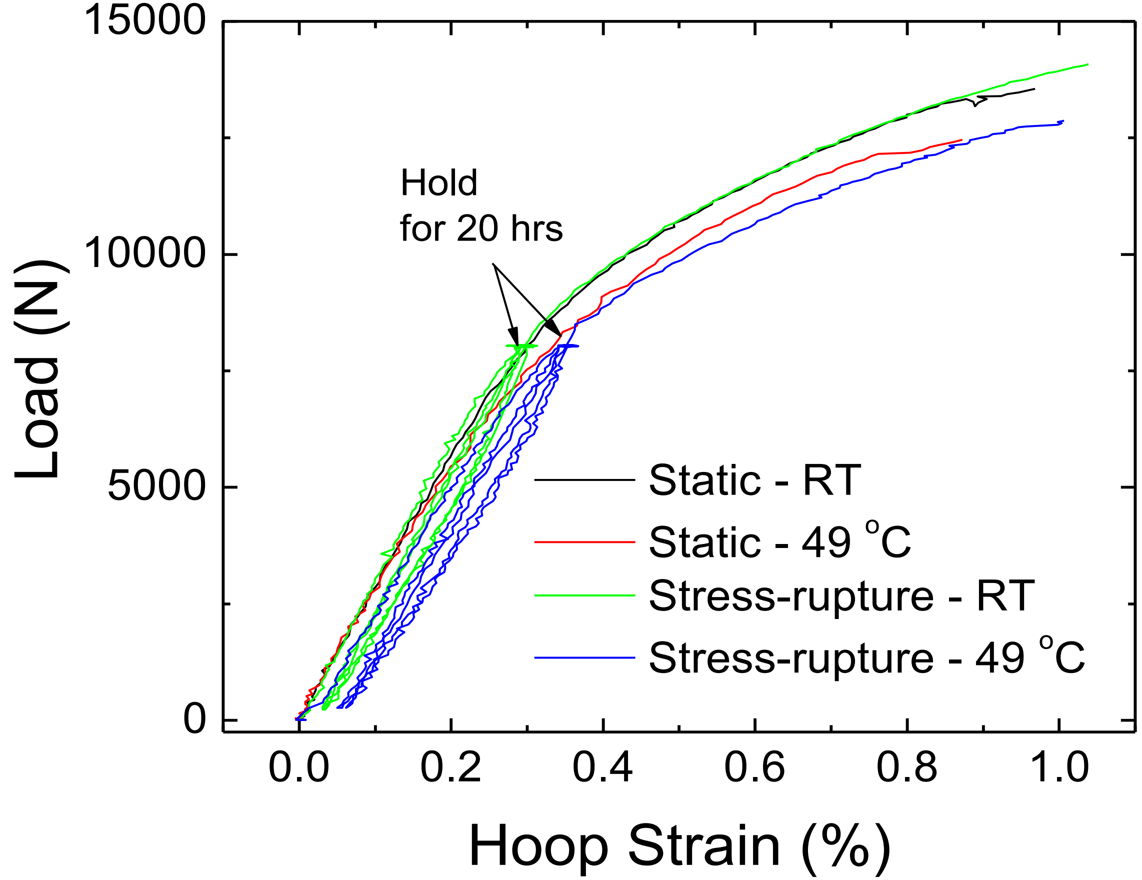
Stress Rupture of CNT Composites

- Stress-rupture: 0 N → proof load → 222 N → proof load → hold for 20 hrs → 222 N → load to failure



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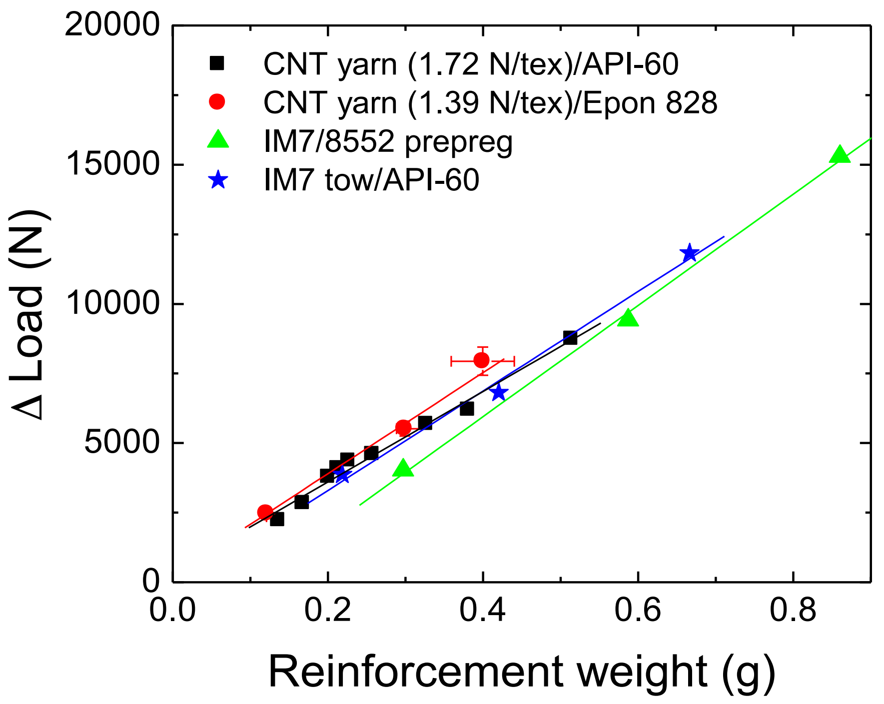
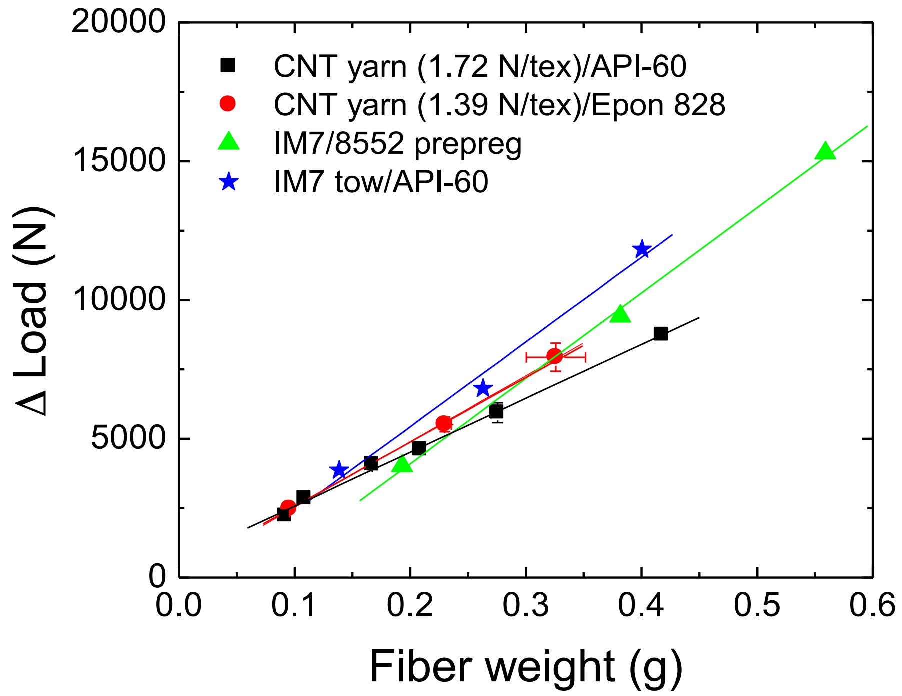
Benchmarking Mechanical Performance of CNT Composites





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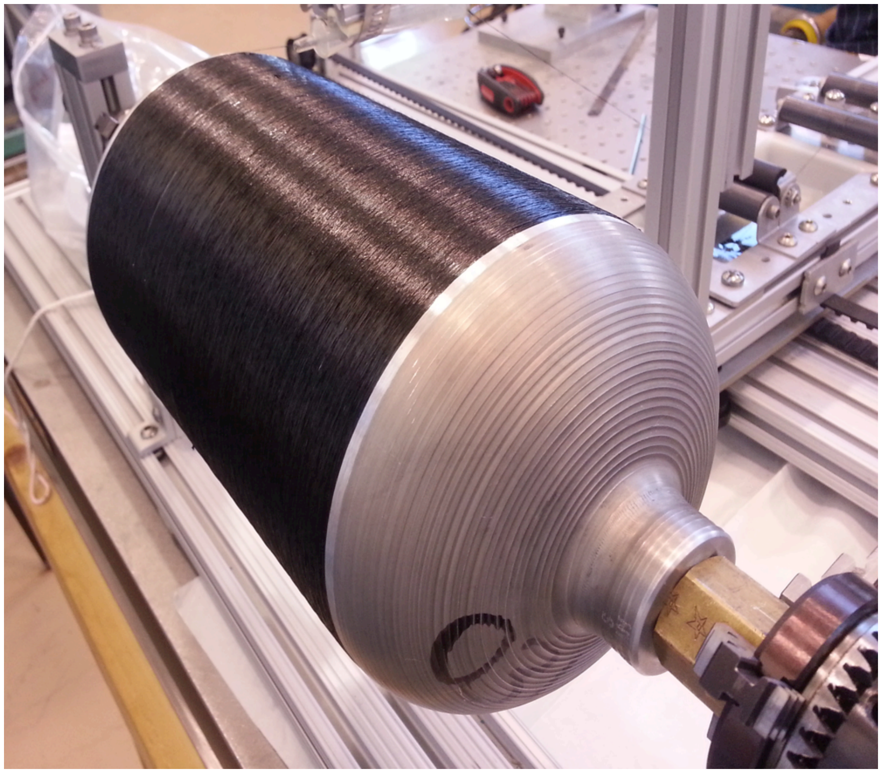
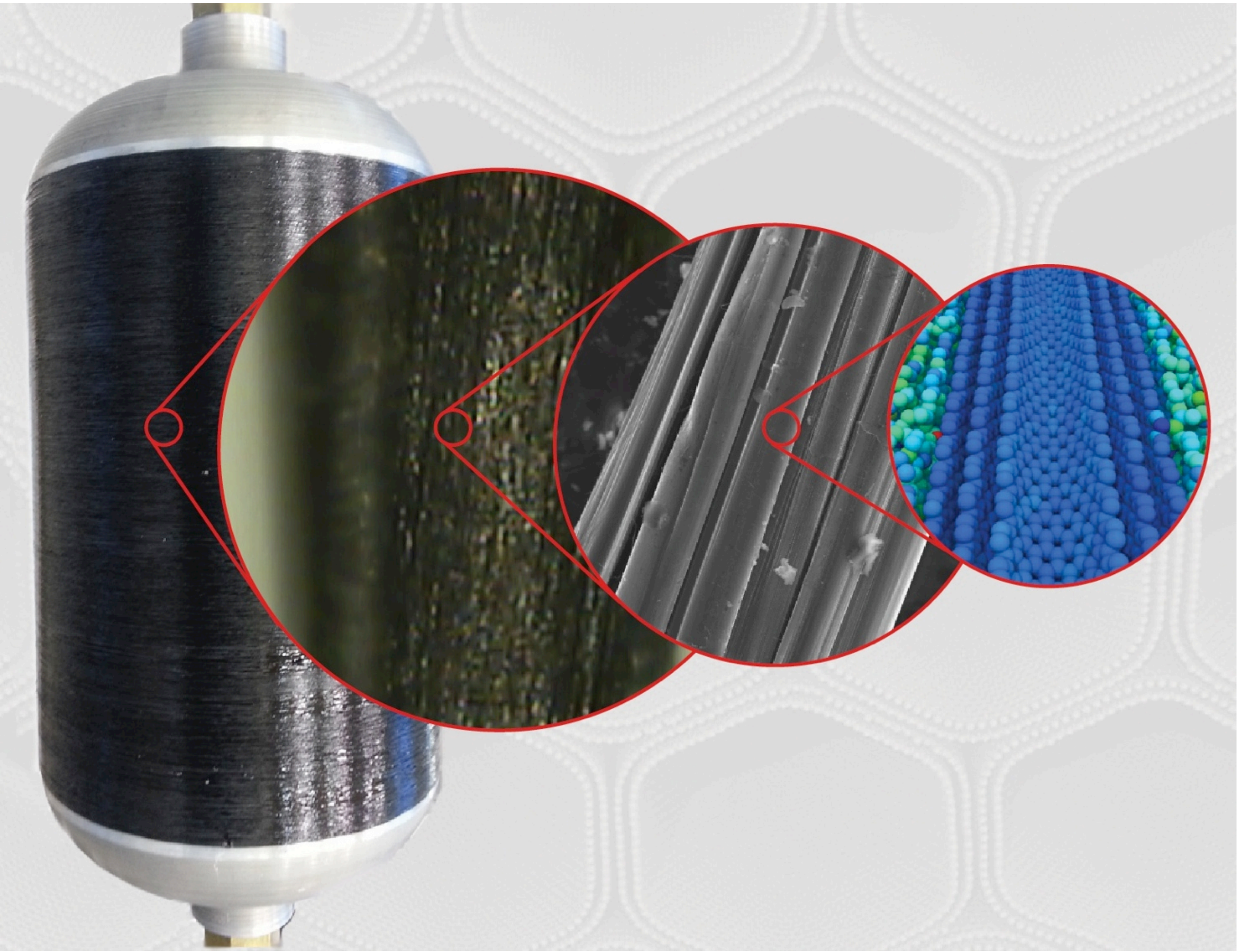
Epon 828/CNT Yarn Composite Overwrapped Pressure Vessel



2 Layers @ 13.3 N of winding tension

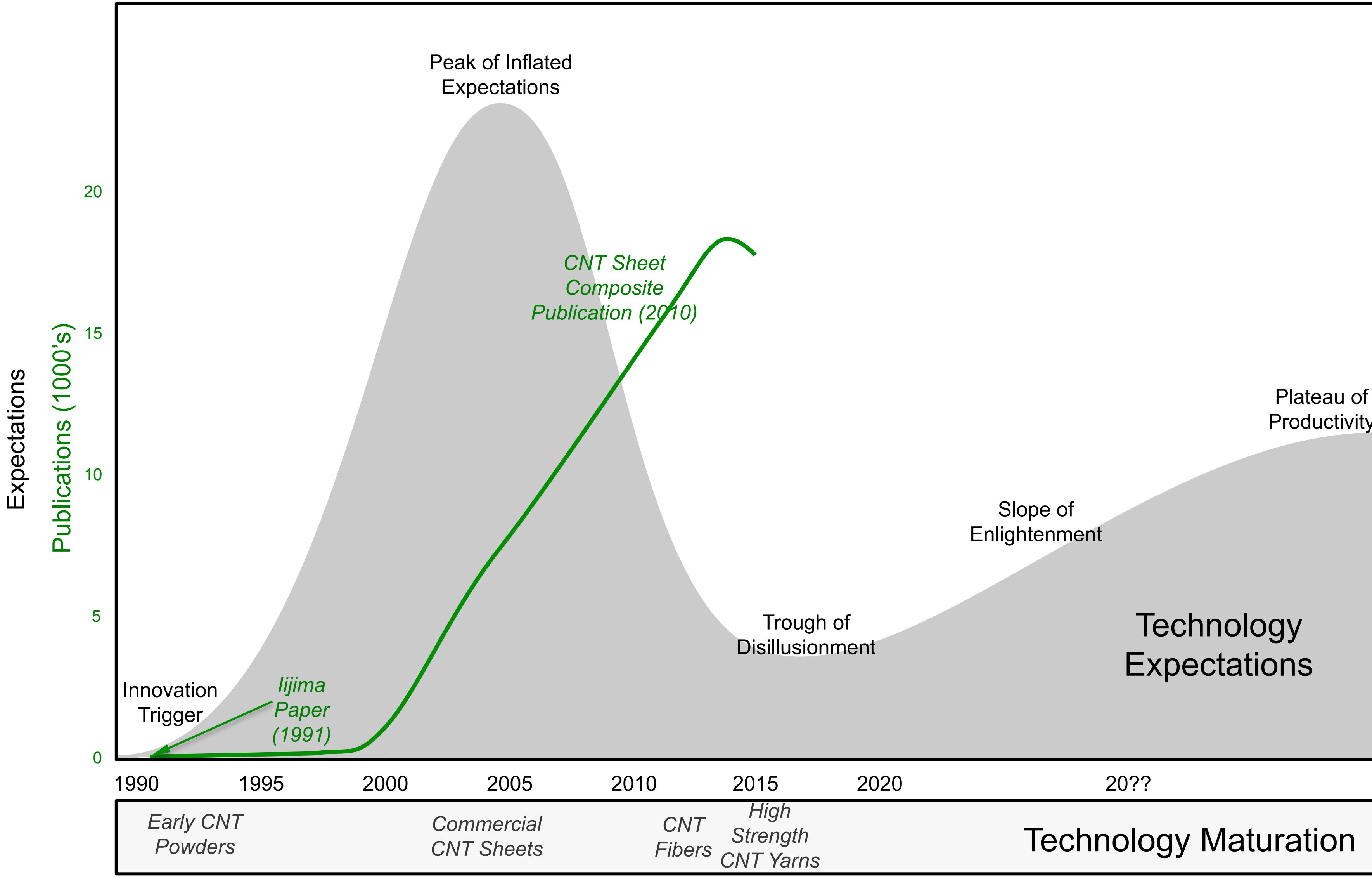
Kim, Jae-Woo, Godfrey Sauti, Roberto J. Cano, Russell A. Wincheski, James G. Ratcliffe, Michael Czabaj, Nathaniel W. Gardner, and Emilie J. Siochi. "Assessment of Carbon Nanotube Yarns as Reinforcement for Composite Overwrapped Pressure Vessels." Composites Part A: Applied Science and Manufacturing (2016).

CNT Composites – Modeling to Application



Sounding Rocket Demo

Carbon Nanotube Gartner Hype Cycle



3D Printing Incubator Team

CNT Yarn Feedstock

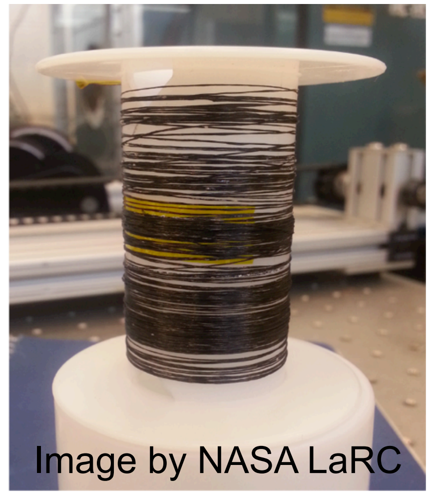
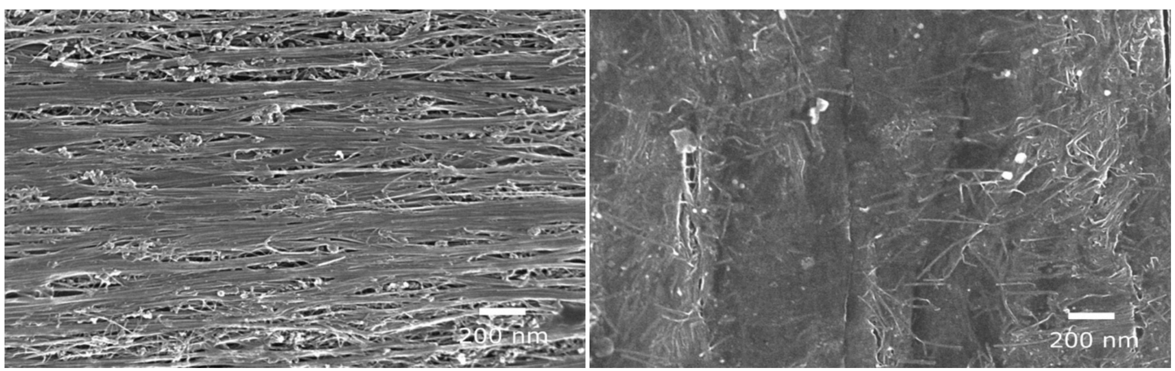


Image by NASA LaRC



Advantages Offered by CNT Yarn Feedstock – Turn Radius

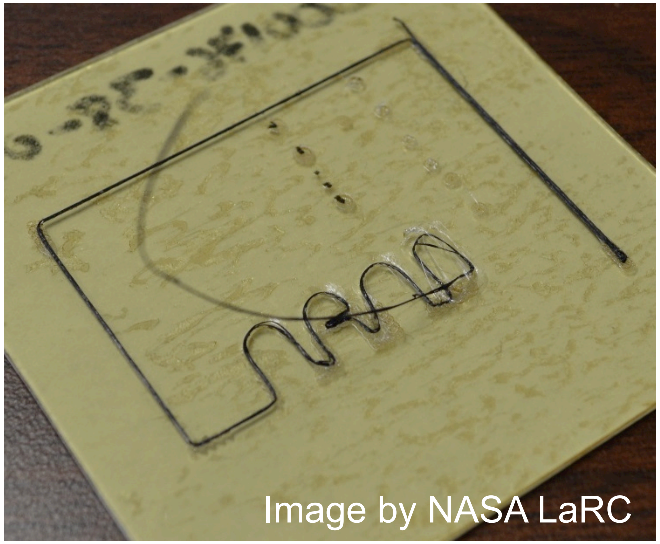


Image by NASA LaRC

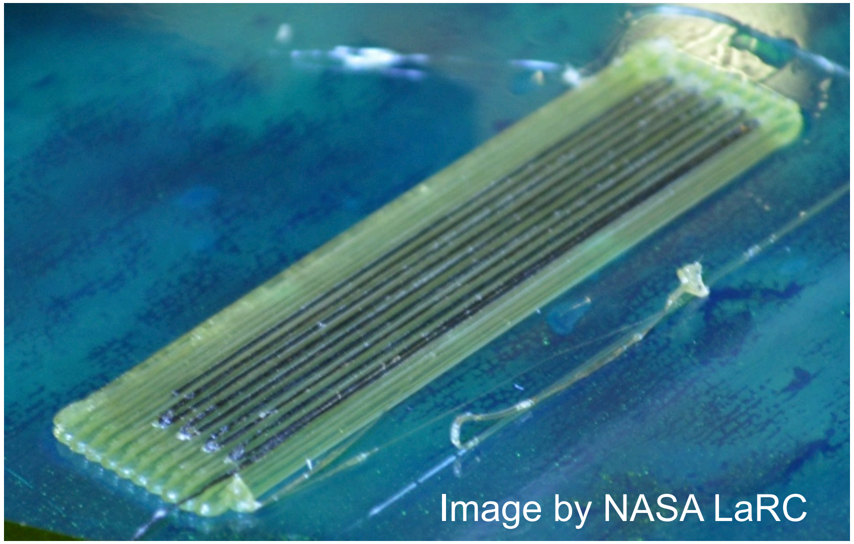
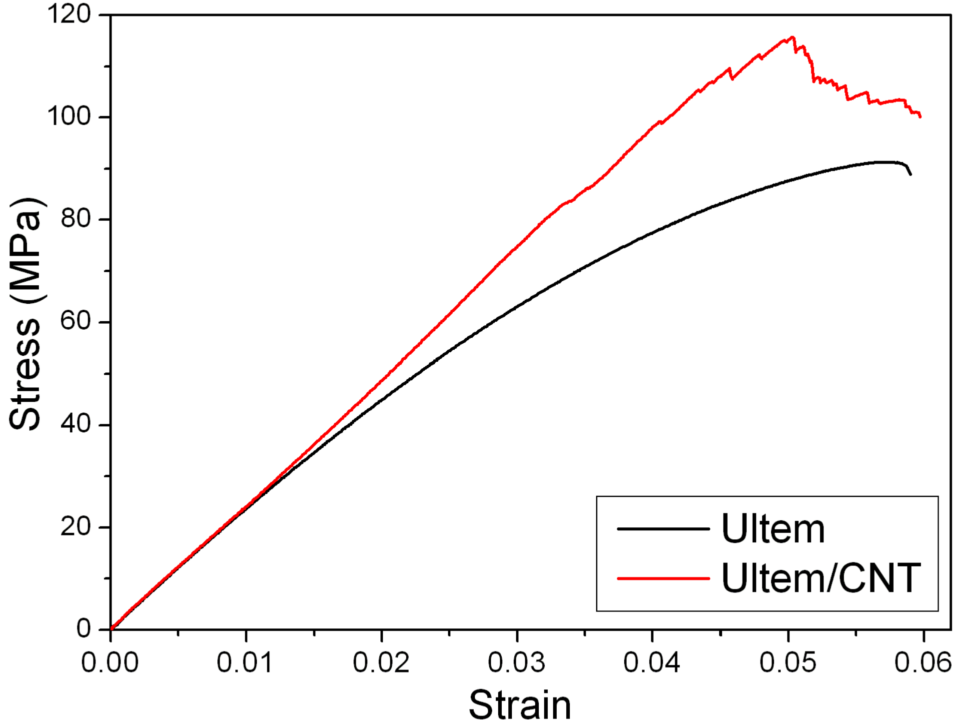
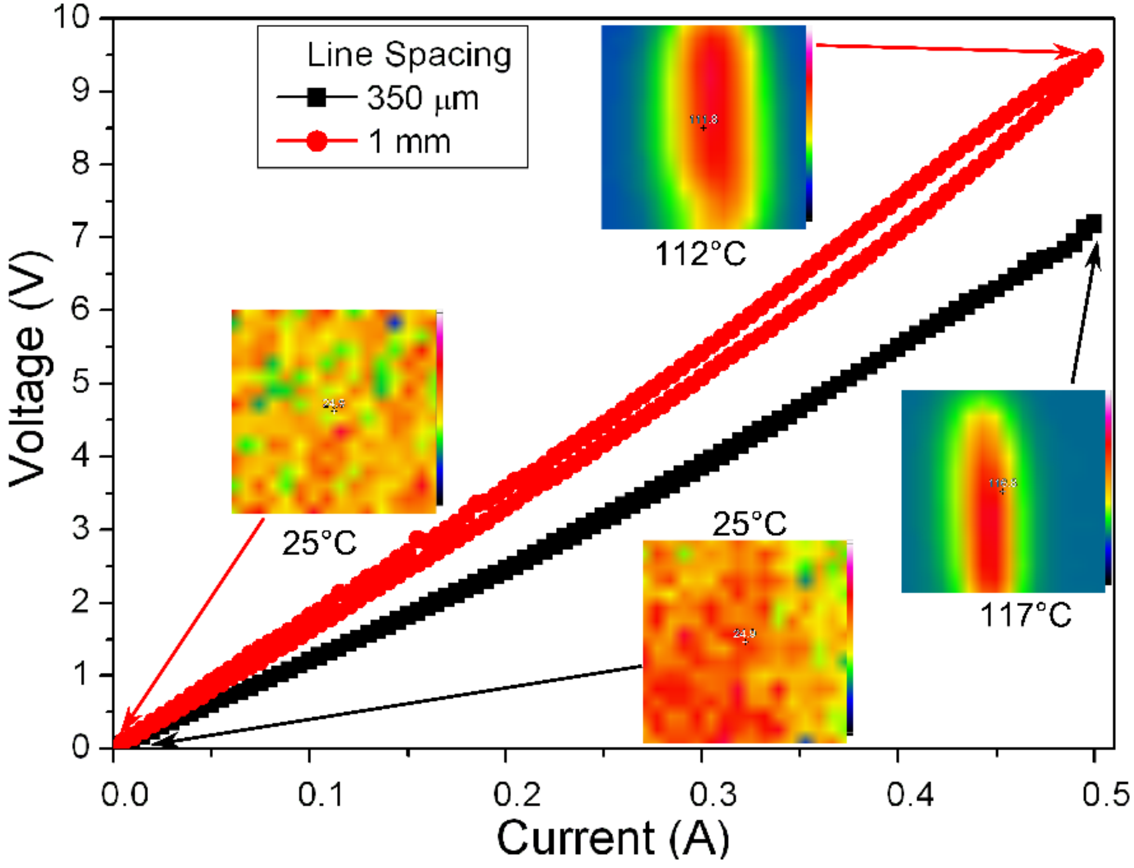


Image by NASA LaRC

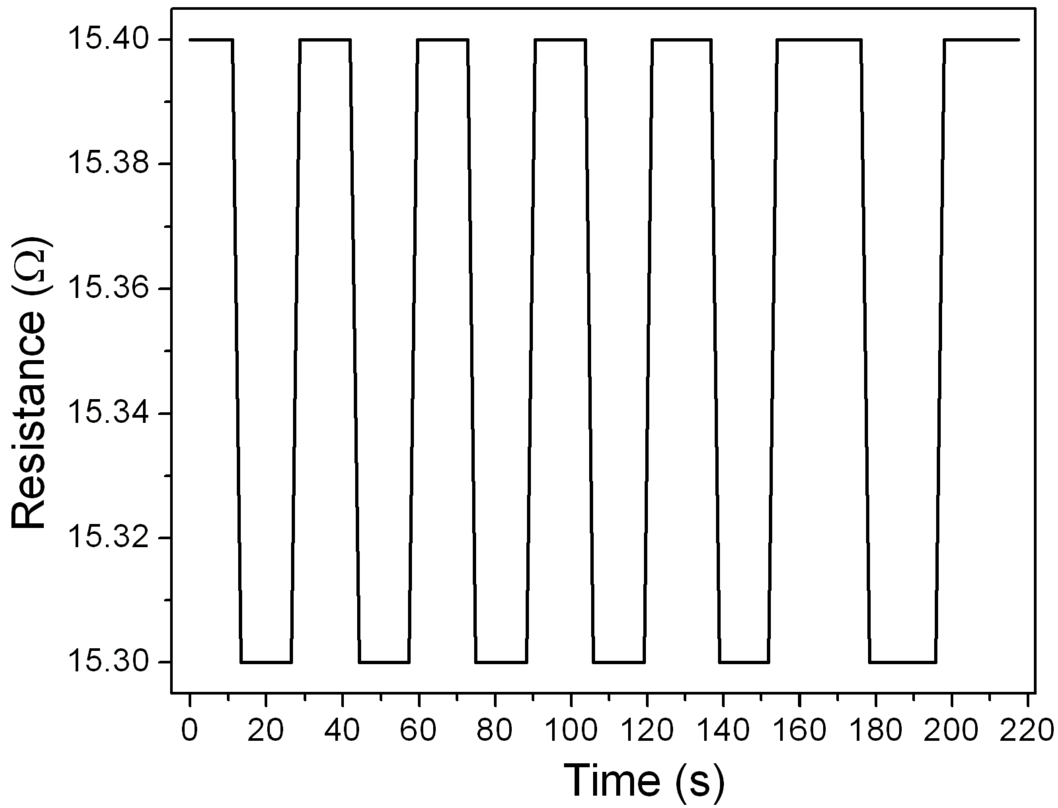
Advantages Offered by CNT Yarn Feedstock – Mechanical Reinforcement



Advantages Offered by CNT Yarn Feedstock – Embedded Heating



Advantages Offered by CNT Yarn Feedstock – Embedded Sensing



Advantages Offered by CNT Yarn Feedstock – Embedded Conductive Paths

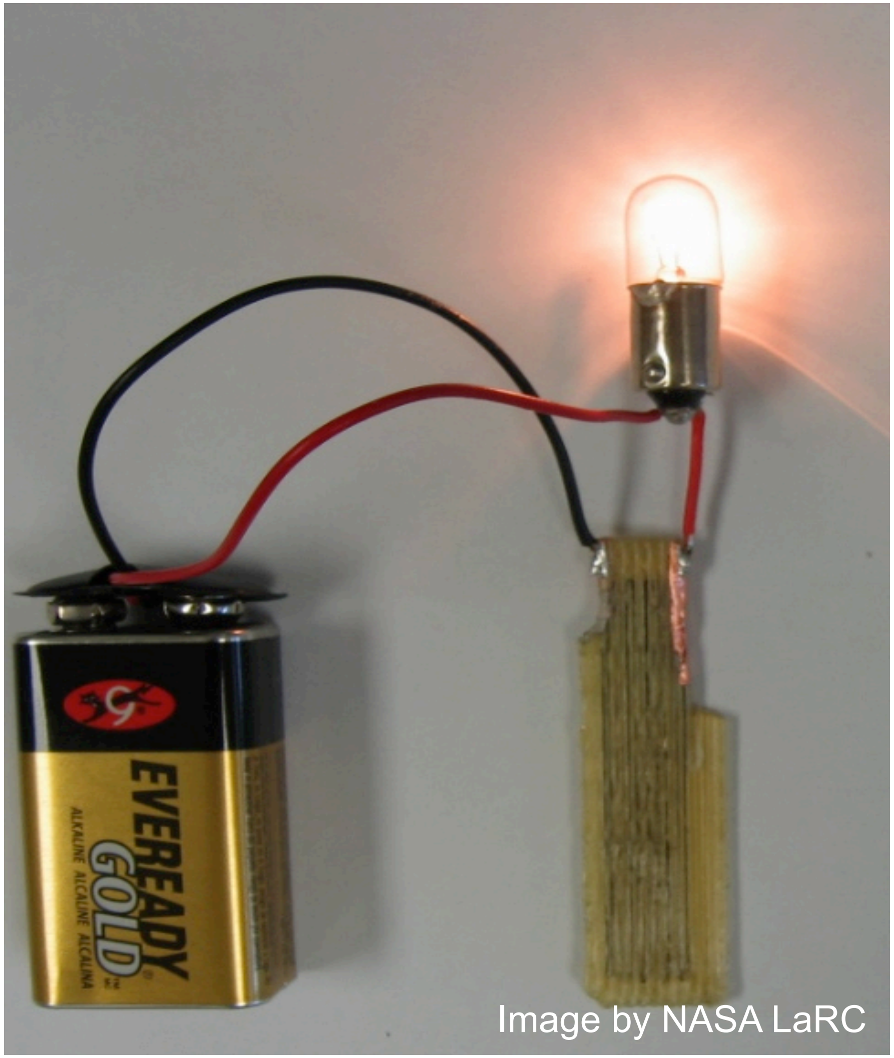


Image by NASA LaRC

Engineered Surfaces for Mitigation of Insect Residue Adhesion

Christopher J. Wohl, Joseph G. Smith Jr. , John M. Gardner, Ronald K. Penner, John W. Connell, Emilie J. Siochi

Acknowledgements

BART Studies:

- Dan Neuhart, Marlyn Andino, Donald Day, Paul Bagby, Michael Leonetti

Flight Tests:

- Northrop Grumman: Anne Bender, Chris Harris, Andrea Korntheuer, Barry Hawkins
- Scaled Composites: Ben Harvey, Mark "Forger" Stuckey, Phillip Grassa, John Marion
- AFRL: Gary Dale, Nate Decker
- Falcon Pilots: Richard Yasky, Gregory Slover, Les Kagey
- Ground Support: Dean Riddick, Rob White, Dale Bowser, Michael Alexander, Jereme Doss, Dawson Connell, Allison Crow

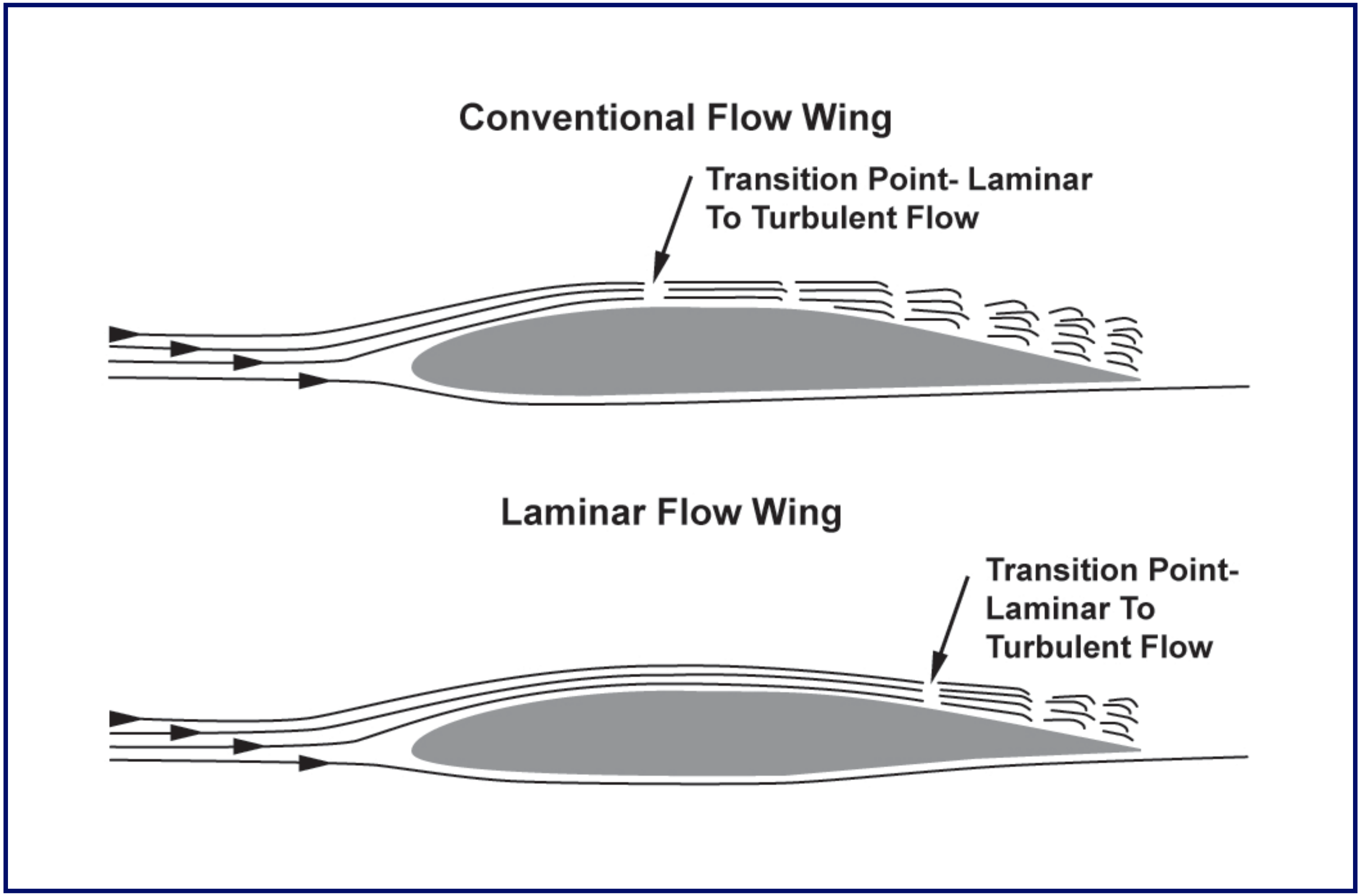
Other Support:

- John Hopkins, LaRC: Laser Ablation Panel Fabrication

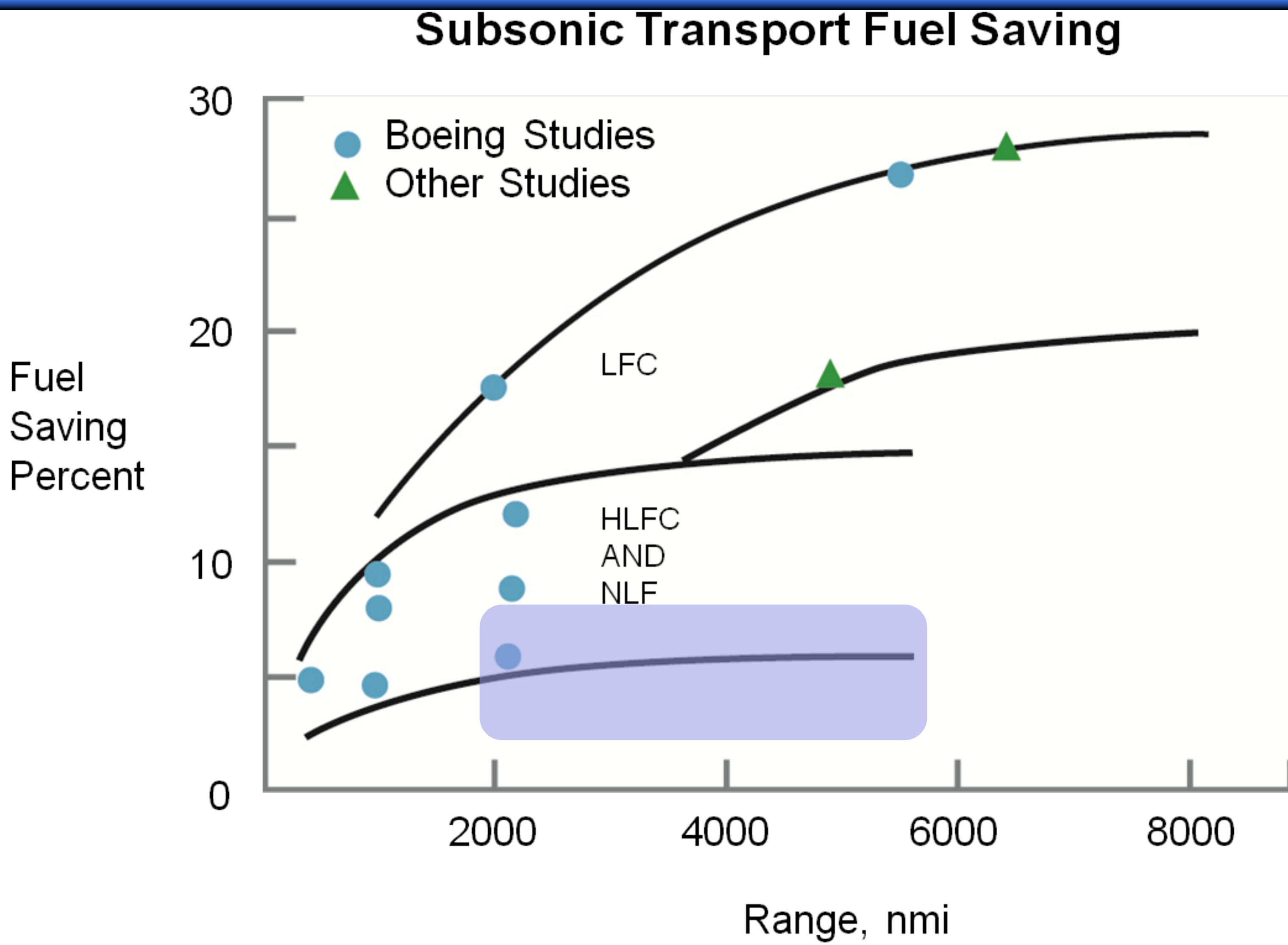
Scientific Discussion:

- Rudy King, Tony Washburn

Laminar Flow

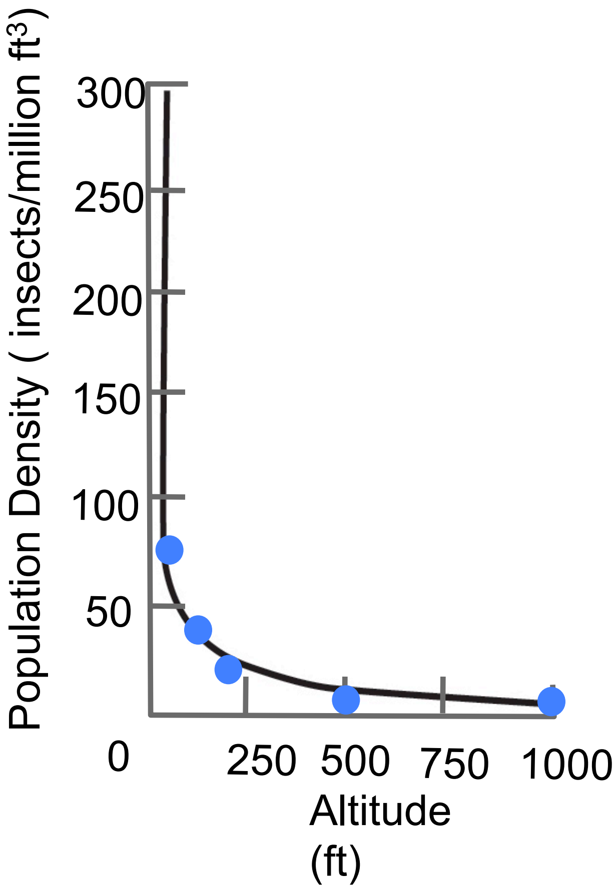


Motivation for Laminar Flow Control



Kirchner, M.E. NASA CP-2487, 1987, Part 1, pp. 24-44.

Objective



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC97–44358–2 Date: December 29, 1997 Photo By: Tony Landis

DC–8 Airborne Laboratory arrival at NASA Dryden

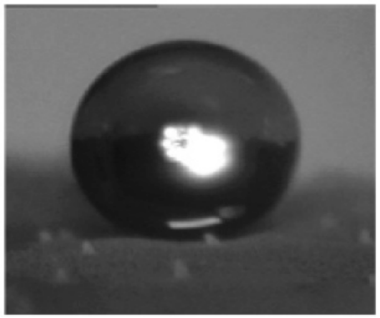
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED04–0056–71 Date: March 6, 2004 Photo By: Jim Ross

NASA's DC–8 flying laboratory takes off from Juan Santamaria International Airport in San Jose, Costa Rica, on NASA's AirSAR 2004 campaign.

To design an engineered surface that prevents insect residue adhesion under take-off and landing conditions.

Bragg, M.G. and Maresh, J.L. AIAA Paper no. 84-2170, 1984.

Evaluation of Engineered Surfaces



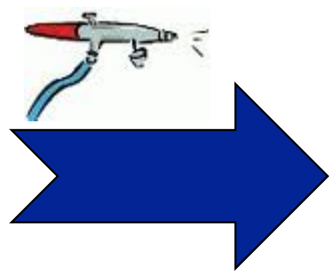
Screen commercial and experimental materials using contact angle goniometry.

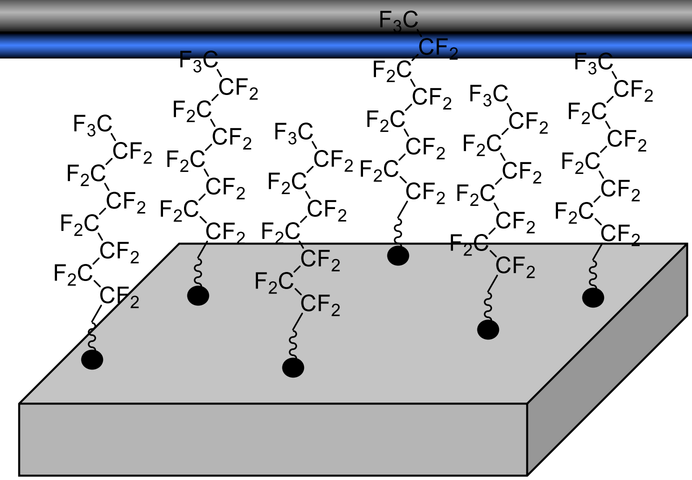
Downselect promising coatings for wind tunnel testing.

Flight test candidate coatings down-selected from wind tunnel tests.

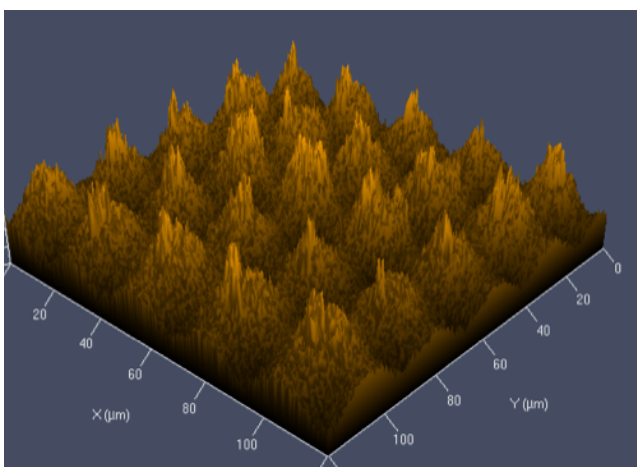
Engineered Surfaces

Aluminum Substrate

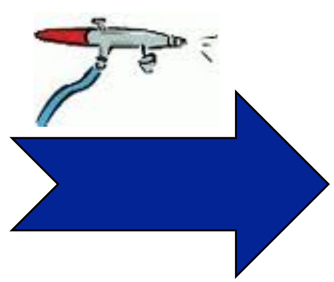


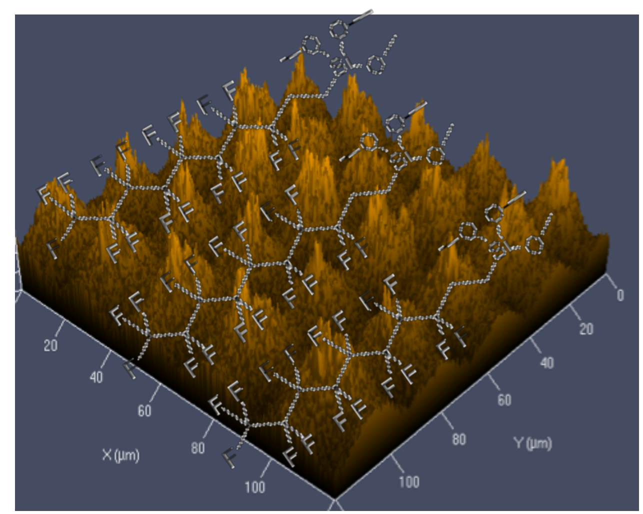


Low Surface Energy Aluminum Substrate



Laser Ablated Aluminum Substrate



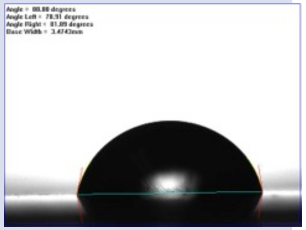
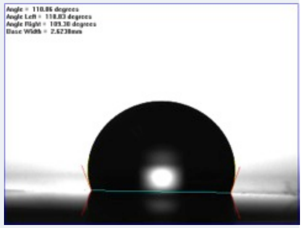
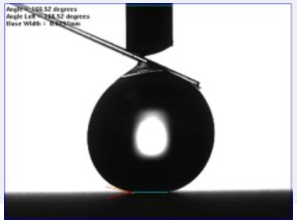


Coated Laser Ablated
Aluminum Substrate

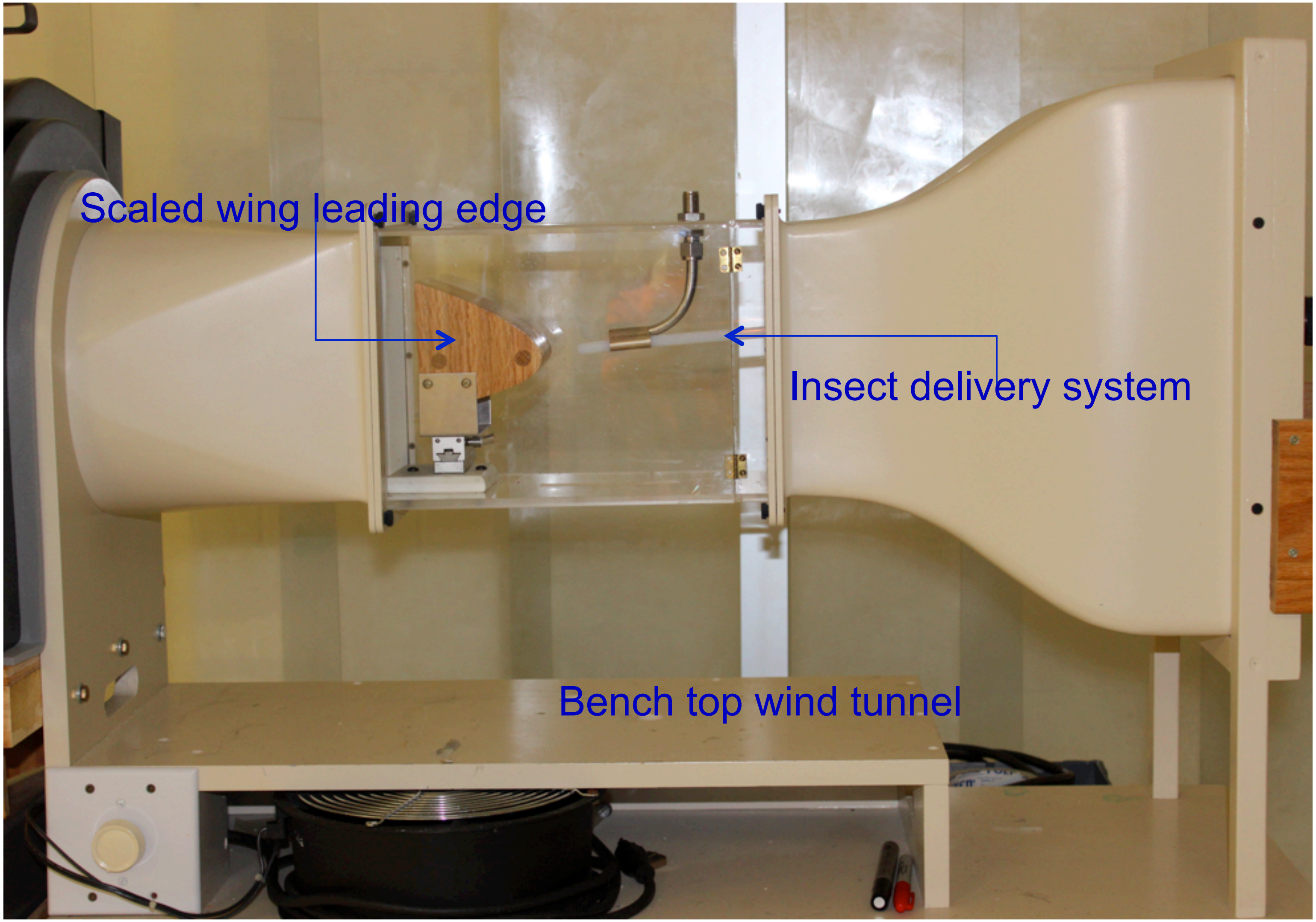
Influence of Surface Characteristics on Surface Energy

Chemical Change

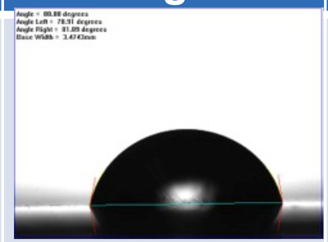
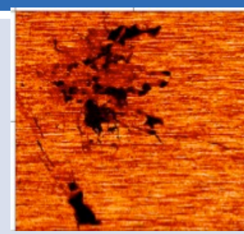
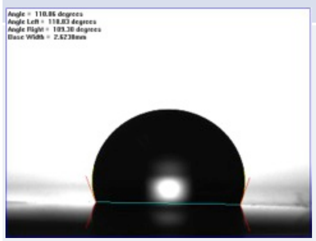
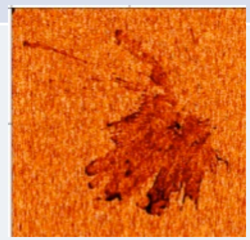
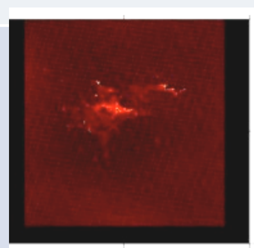
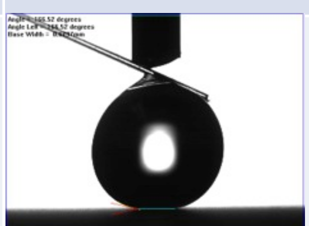
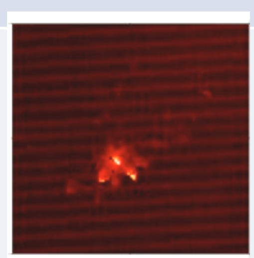
Topographical Change

Surface	Contact Angle
Aluminum Control	
Hydrophobic Coating	
Laser Patterned	
Coated Laser Patterned	

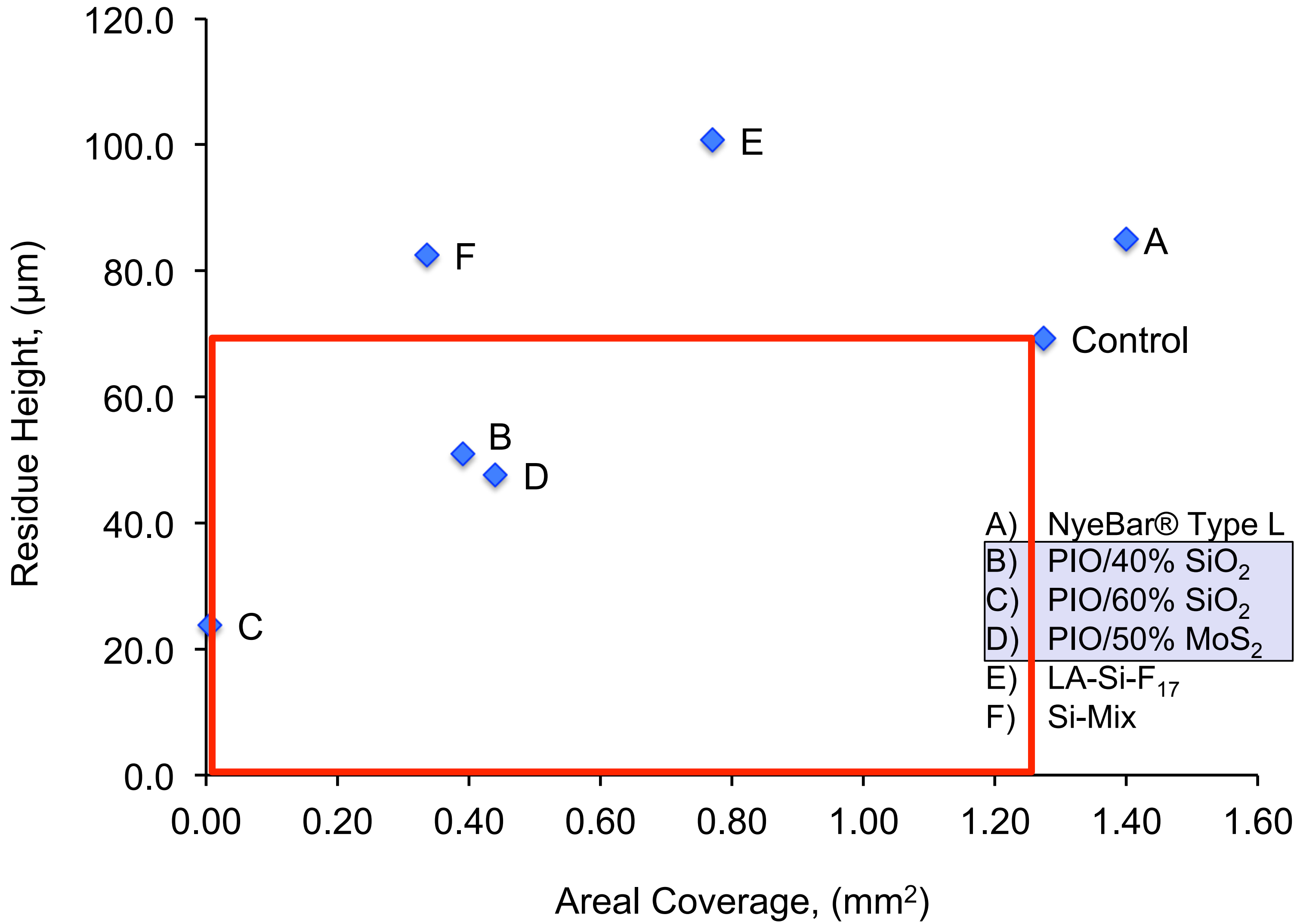
Lab Scale Bug Gun



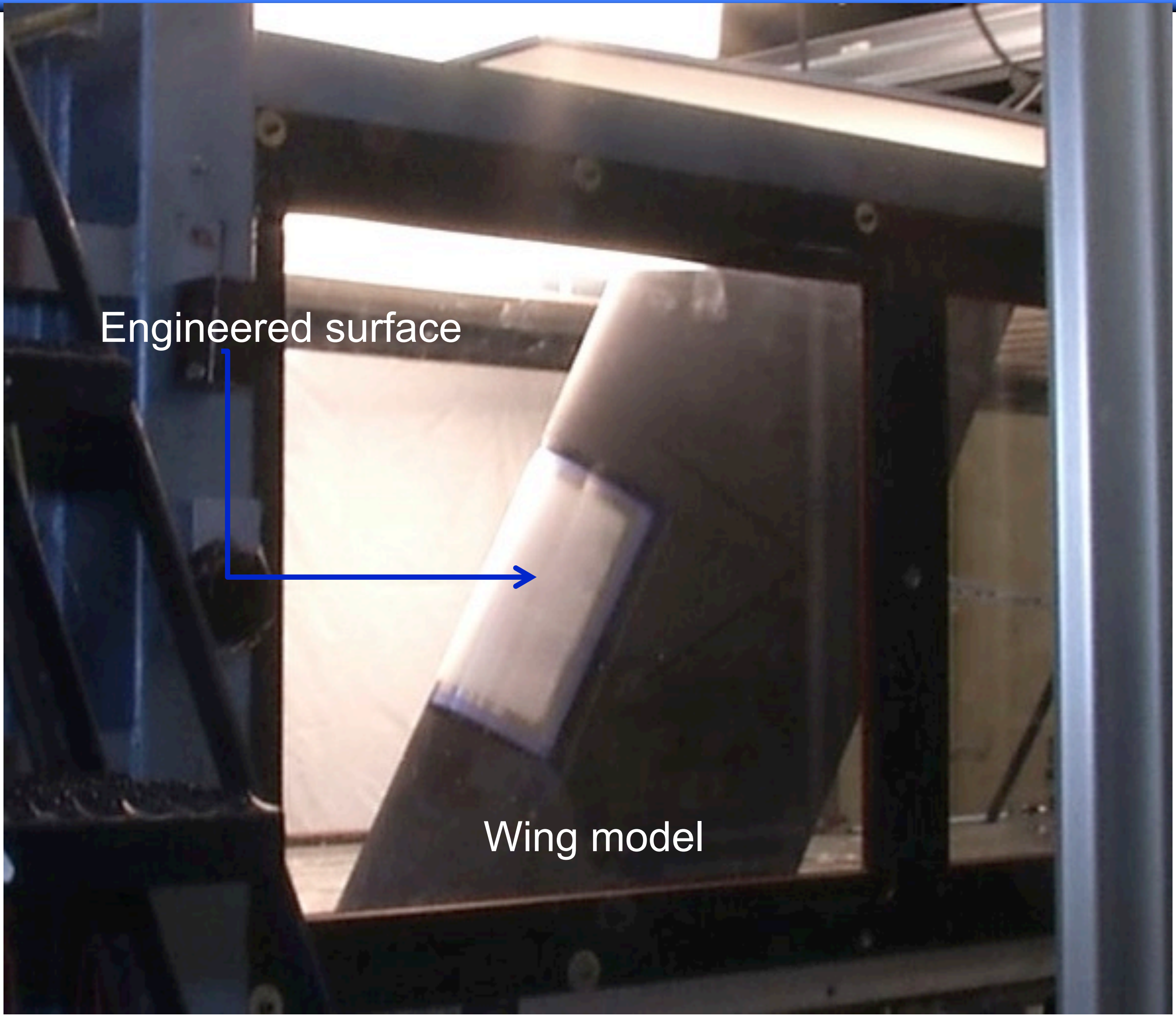
Influence of Surface Characteristics on Insect Residue Adhesion

Surface	Contact Angle	Residue Area	Areal Coverage (mm²)	Residue Height (µm)
Aluminum Control			1.38 ± 0.49	70 ± 4
Hydrophobic Coating			0.71 ± 0.30	66 ± 4
Laser Patterned			1.22 ± 0.10	66 ± 5
Coated Laser Patterned			0.45	62

Lab Scale Fruit Fly Test Results

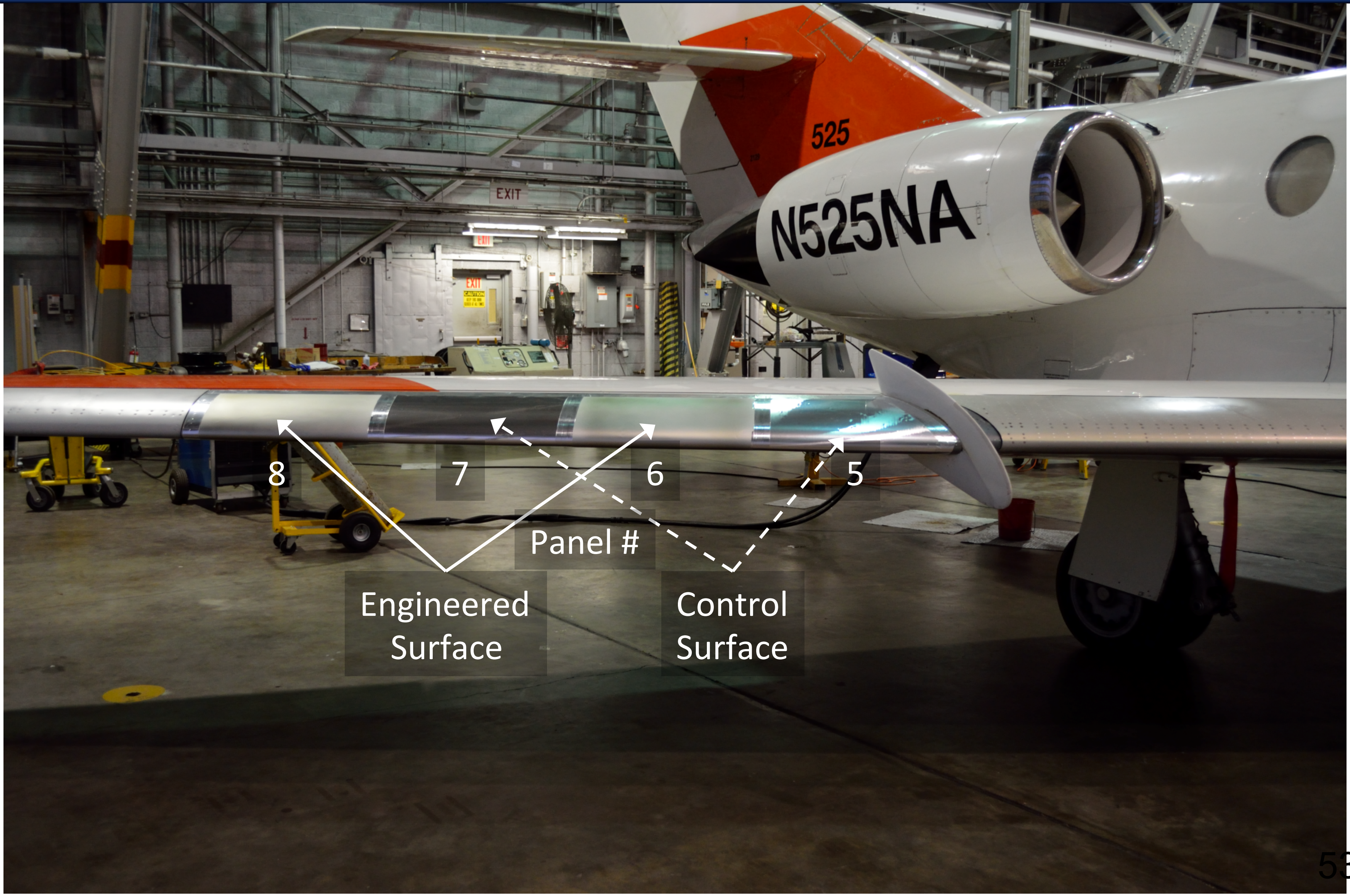


Model for BART Insect Adhesion Tests

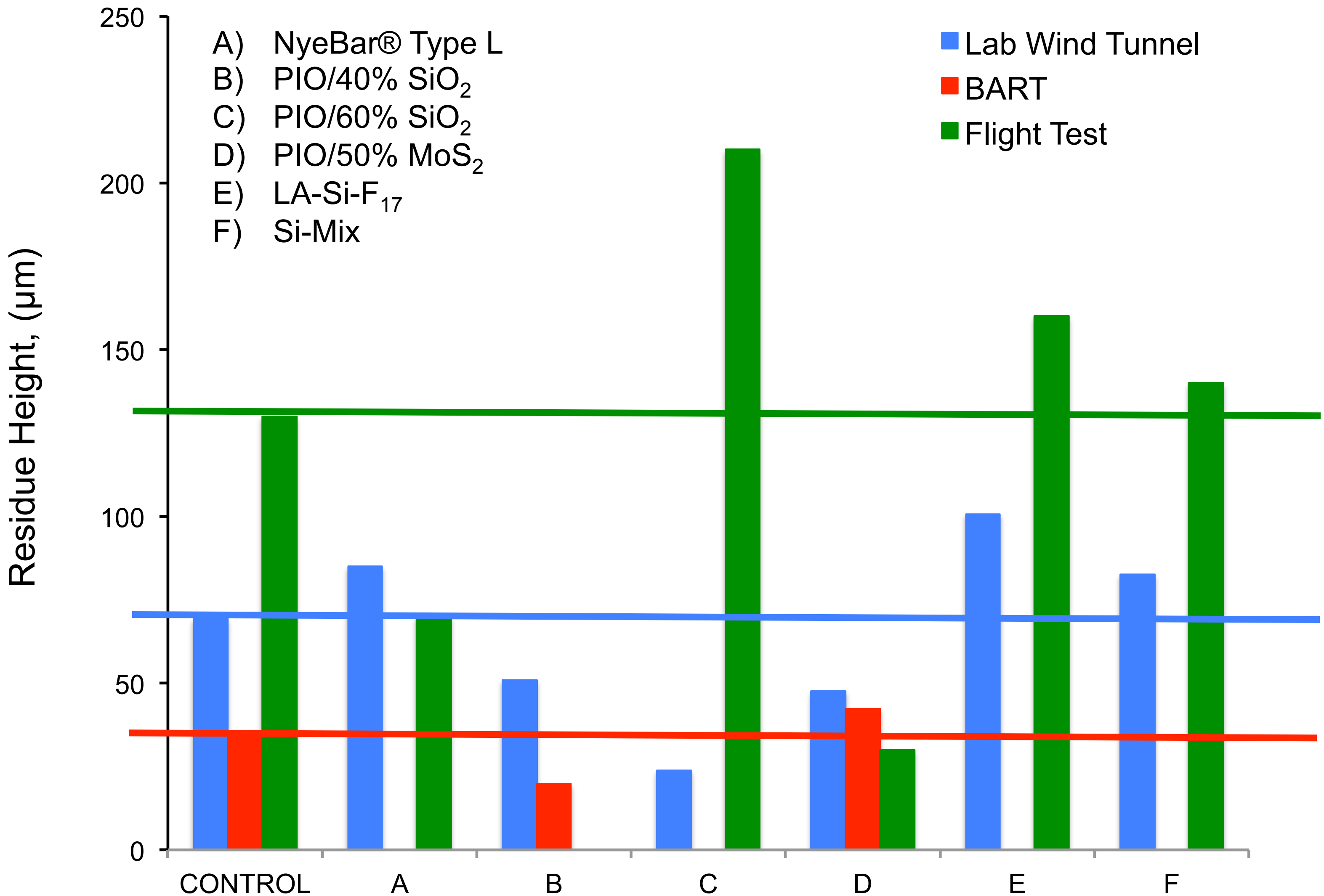


Falcon Flight Testing

Falcon Flight Testing



Summary of Test Results

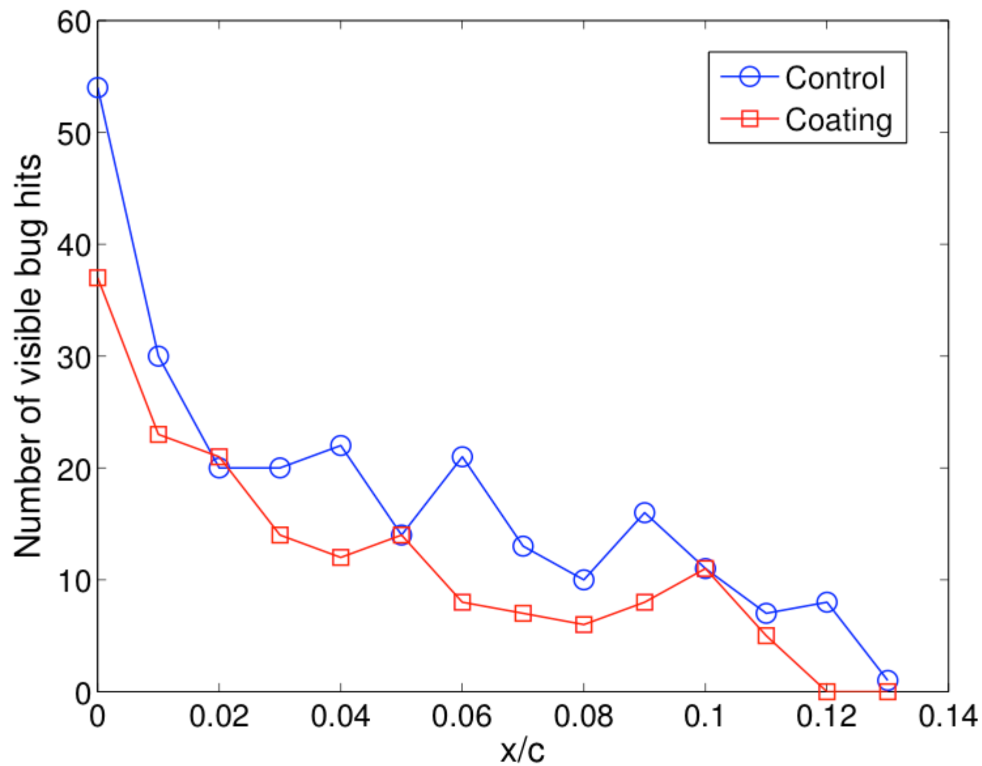


EcoDemonstrator Flight Testing

EcoDemonstrator Flight Testing

Counting Insect Impacts on Engineered Surface

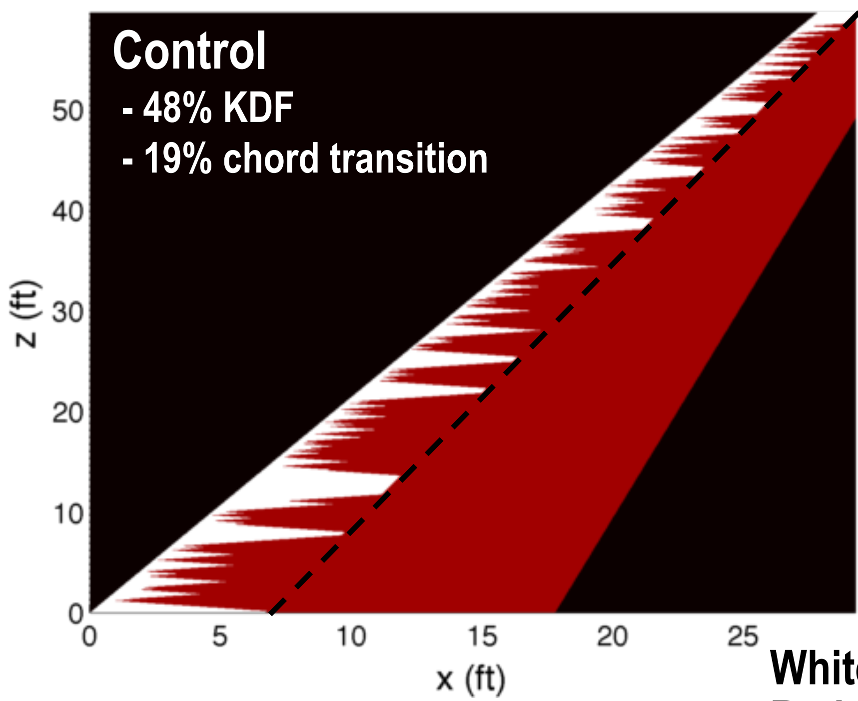
Post flight assessment of insect accretion

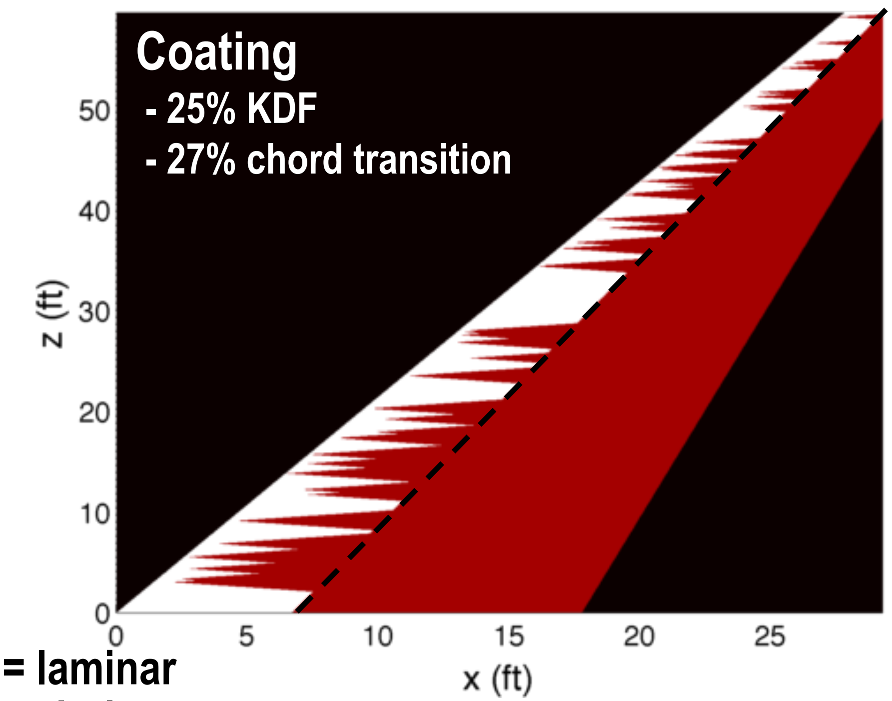


Sample insect impact data from flight test

Systems Benefits – Single Aisle Aircraft

- Based on bug height distributions and bug splat counts from the ecoDemonstrator flight test (first 12% chord).
- Computed boundary layer profiles from a generic NLF wing was used to compute Re_{kk}
- Using the assumed turbulence spreading (5° half angle), calculate the knock-down factor (KDF) with and without the coating
  - KDF = (% laminar flow baseline - % laminar flow with insects)/(% laminar flow baseline)*100%
- Perform Monte-Carlo simulation (~1000 iterations) to calculate the average KDF





White = laminar
Red = turbulent

Black dashed line denotes initial assumed transition location (36% chord)


Thank You